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Effects and Mechanisms of Working Memory Training: A Review

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Abstract

Can cognitive abilities such as reasoning be improved through working memory training? This question is still highly controversial, with prior studies providing contradictory findings. The lack of theory-driven, systematic approaches and (occasionally serious) methodological shortcomings complicates this debate even more. This review suggests two general mechanisms mediating transfer effects that are (or are not) observed after working memory training: enhanced working memory capacity, enabling people to hold more items in working memory than before training, or enhanced efficiency using the working memory capacity available (e.g., using chunking strategies to remember more items correctly). We then highlight multiple factors that could influence these mechanisms of transfer and thus the success of training interventions. These factors include (1) the nature of the training regime (i.e., intensity, duration, and adaptivity of the training tasks) and, with it, the magnitude of improvements during training, and (2) individual differences in age, cognitive abilities, biological factors, and motivational and personality factors. Finally, we summarize the findings revealed by existing training studies for each of these factors, and thereby present a roadmap for accumulating further empirical evidence regarding the efficacy of working memory training in a systematic way.

Keywords: working memory capacity, training, transfer

Effects and Mechanisms of Working Memory Training: A Review

In recent years, an intense debate arose over the effectiveness of computerized working memory (WM) training (e.g., see Klingberg, 2012; Shipstead, Hicks, & Engle 2012). WM is a cognitive system providing temporary access to representations needed for complex cognition in the present moment. The individual capacity limit of this core ability is assumed to be a largely stable trait, and previous research demonstrated a strong relationship between WM capacity and multiple other cognitive abilities (for an overview, see Feldman Barrett, Tugade, & Engle, 2004). In particular, WM capacity has been established as one of the best predictors for intelligence (Conway, Kane, & Engle, 2003; Engle, Kane, & Tuholski, 1999; Engle, Tuholski, Laughlin, & Conway, 1999; Kyllonen & Christal, 1990; Oberauer, Su¨ß, Wilhelm, & Wittmann, 2008; Su¨ß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). On the other side, impairments in WM are often observed in neurological conditions such as attentiondeficit hyperactivity disorder (ADHD, Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) or learning disabilities (Alloway, 2009). Consequently, the prospect of training WM and thereby not only expanding WM capacity but also improving reasoning abilities or helping to overcome cognitive deficits stimulated a growing number of studies evaluating effects of WM training (for reviews, see Buschkuehl & Jaeggi, 2010; Klingberg, 2010; Morrison & Chein, 2011). Several studies indeed reported increased reasoning scores following different forms of WM training, indicating that fluid intelligence—so far believed to be a fixed trait—could be malleable after all (Borella, Carretti, Riboldi, & De Beni, 2010; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi et al., 2010; Klingberg et al., 2005, Klingberg, Forssberg, & Westerberg, 2002; Olesen, Westerberg, & Klingberg, 2004; Schmiedek, Lo¨vden, & Lindenberger, 2010; von Bastian & Oberauer, 2013). These promising findings stand, however, opposite to an increasing number of studies not finding any evidence for change in reasoning (Brehmer, Westerberg, & Bäckman, 2012; Chein & Morrison, 2010; Dahlin, Nyberg, Bäckman, & Stigsdotter Neely, 2008; Holmes, Gathercole, & Dunning, 2009; Owen et al., 2010; Redick et al., 2013; Richmond, Morrison, Chein, & Olson, 2011; von Bastian, Langer, Jäncke, & Oberauer, 2013), and a first meta-analysis therefore concluded that WM training effects do not generalize to reasoning (Melby-Lervåg & Hulme, 2013; but see Cogmed, 2013).

Besides serious methodological issues reviewed elsewhere (Conway & Getz, 2010; Shipstead, Redick, & Engle, 2010, 2012), multiple additional factors are potentially responsible for these inconsistent if not contradictory findings in WM training research (see Fig. 1). First, we suggest that change in cognitive performance can be mediated by two general mechanisms: enhanced WM capacity or enhanced WM efficiency. As illustrated in Fig. 1, progress during training could act as a moderator impacting these mechanisms of transfer. Second, we will examine the existing evidence concerning additional factors potentially influencing both training and transfer gains such as intervention-specific features (e.g., training tasks and conditions) and individual differences (e.g., in cognitive abilities or in personality). Finally, we follow with a summary of existing research. Table 1 categorizes all WM training studies included in this review alongside the factors illustrated in Fig. 1.

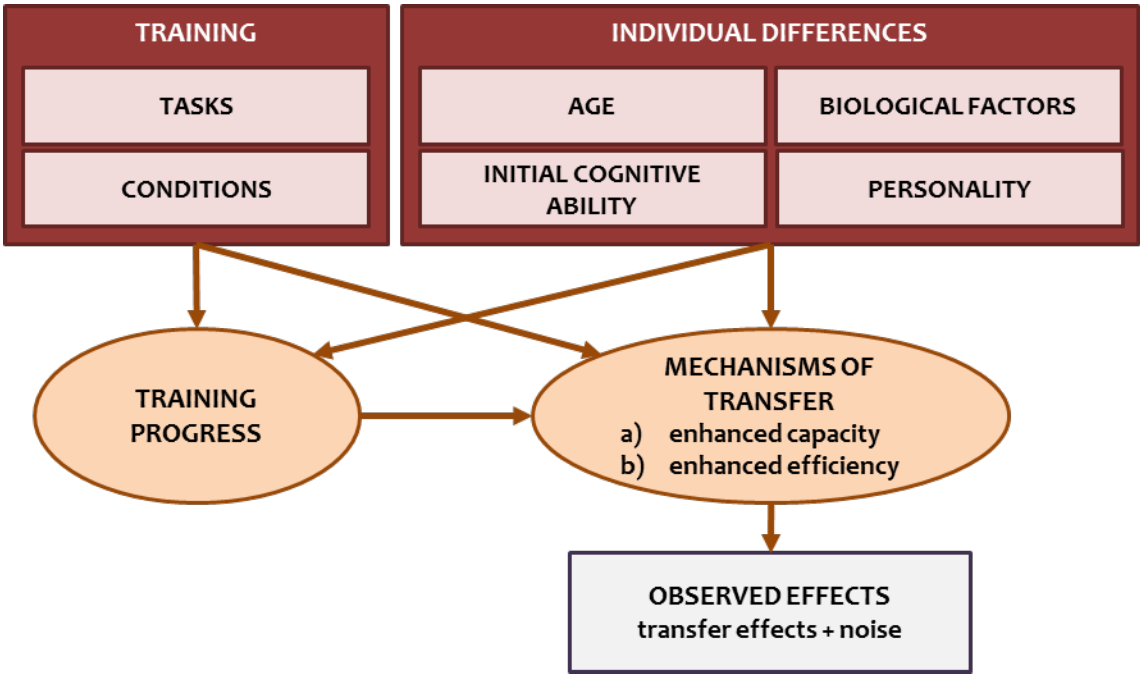

Figure 1. Factors possibly influencing outcomes of WM training.

MECHANISMS OF TRANSFER

Training-induced change can generally be caused by two possible processes: expanded WM capacity or enhanced WM efficiency. An increase in WM capacity (i.e., the ability to hold more items simultaneously in WM after than before training) theoretically results from a prolonged cognitive demand that exceeds existing capacity limits, thereby inducing changes in brain regions affecting the limiting factors of WM capacity (cf. Lövden, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010). Enhanced WM capacity should then yield performance increases in cognitive abilities drawing on the same structural resources as WM, often argued as being reflected by neuronal overlap (i.e., overlapping activations during execution of cognitive functions, cf. Dahlin, Stigsdotter Neely, Larsson, Bäckman, & Nyberg, 2008). Behaviorally, it is assumed that expanded WM capacity establishes itself by co-occurring performance increases in untrained tasks that share variance with the training tasks (Klingberg, 2010). Observed improvements in untrained tasks also measuring WM are typically classified as "near transfer", whereas improvements in tasks measuring other cognitive abilities correlated with WM capacity (e.g., reasoning) are termed "far transfer". In general, the stronger the correlation between WM capacity and this other cognitive ability, the larger the transfer effect can be expected. As WM capacity strongly correlates with a wide range of cognitive abilities, transfer based on expanded WM capacity should be very broad and manifest in multiple measures independent of material and structure of the tasks employed—ideally on the level of latent abilities (cf. McArdle & Prindle, 2008; Schmiedek et al., 2010). So far, only few WM training studies established such broad transfer (e.g., Borella et al., 2010 in older adults; Schmiedek et al., 2010 mainly in younger adults).

Regarding neural correlates of capacity-based transfer, effective training interventions should induce brain signatures that are observed in high-capacity individuals, and that are observed independently of the specific training tasks (e.g., changes in activity of the multiple-demand network, see Duncan, 2010, or changes in resting-state activity). For example, in a recent study in our laboratory, we observed training-induced changes in functional brain networks associated with WM, which shifted trainees' network characteristics in resting state more in the direction of high-capacity individuals (Langer, von Bastian, Wirz, Oberauer, & Jäncke, 2013).

Instead of expanded capacity, transfer can also be mediated by the acquisition of knowledge and skills (i.e., strategy usage, chunk learning, and automatization of basic processes) during training, leading to a more efficient use of the WM capacity available. In contrast to expanded capacity, enhanced efficiency is expected to be material- and/or process-specific. For example, one possibility to enhance efficiency is to chunk subsets of items to remember them more easily (cf. Ericsson & Kintsch, 1995). This kind of knowledge should transfer only to tasks using the same class of materials. Another possibility is the acquisition of a strategy suited for a specific task paradigm, such as the n-back task or the complex span task. This kind of strategy knowledge would be expected to transfer only to new versions of the same paradigm. Previous studies indeed indicate that strategy use contributes to performance in complex span tests (Dunlosky & Kane, 2007). However, despite often remarkable effects of strategy instruction on performance in the tasks trained (e.g., Carretti, Borella, & De Beni, 2007; Ericsson & Chase, 1982; Karbach, Mang, & Kray, 2010; McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003), usually only limited transfer to tasks with a novel structure and/or material is observed (for a review, see Lustig, Shah, Seidler, & Reuter-Lorenz, 2009).

As knowledge and skills are usually specific and lead to only narrow transfer, it is often argued that far transfer effects are an indicator for the training intervention having not only enhanced efficiency but also expanded WM capacity. However, far transfer effects could also reflect systematic changes in strategy use. This means that general, task-unspecific strategies are acquired during a training intervention which, at least to some extent, are transferred to other paradigms or novel stimulus material and are therefore material-independent but process-specific. For example, optimizing speed-accuracy trade-off settings, or strategically focusing on solving only a sub-sample of items correctly, could be helpful in a broad range of cognitive tests. As some strategies could have such broad effects, it is essential to have a theoretical idea of which strategies could be applied in the training and transfer tasks and how effective these strategies are, so that predictions can be made about their potential range of transfer. If broad and far transfer is to be explained by general strategies, these strategies and their effects must be specified—otherwise, the appeal to general strategies becomes untestable. Hence, to exclude strategy use as an explanation for the presence or the absence of transfer effects, transfer tasks should be chosen based on a set of theoretically well-defined strategies.

In addition to strategy use, WM efficiency could also be improved by a higher level of automatization of the process practiced, thereby releasing cognitive resources for other concurrent demands (cf. Case, Kurland, & Goldberg, 1982). For example, in a complex span paradigm where encoding of memoranda and distractor processing rapidly alternate (cf. Daneman & Carpenter, 1980), task practice could lead to shorter processing times on the distractor task, leaving more free time for refreshing the memoranda (cf. Barrouillet, Bernardin, & Camos, 2004), or for removing interfering distractor representations from working memory (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). Another example for enhanced efficiency is a training-induced decrease in the time needed to move the focus of attention between single items. To date, a few studies have found that training the single-item focus of attention can reduce (but not eliminate) costs in reaction times for switching between objects held in WM (Dorbath, Hasselhorn, & Titz, 2011; Oberauer, 2006; Verhaeghen, Cerella, & Basak, 2004; but see Lilienthal, Tamez, Shelton, Myerson, & Hale, 2013 for a study not finding such improvements in focus switching). A more rapid focus switching is essential for the refreshing of memoranda (Barrouillet et al., 2004) and thus would be expected to result in improved performance in any task that depends on refreshing. Hence, although an increase in automatized information processing clearly enhances efficiency and not capacity, it is plausible to assume that it would also result in some far transfer effects.

In summary, the absence or presence of improved performance in one or multiple cognitive tasks alone is not sufficient to determine whether training induced an increase in WM capacity or efficiency. To distinguish empirically between these two mechanisms of transfer, observed gains have to be evaluated within theoretical frameworks that define capacity and efficiency limits and thus allow for a priori predictions of which type of transfer is expected to occur. For example, one family of recent models conceptualizes WM as a system providing access to a small number of long-term memory representations that are presently needed for complex cognition (Cowan, 1995; Oberauer, 2009), a single one of which is in the focus of attention and hence can be manipulated at the present moment (Garavan, 1998; Oberauer, 2002, 2009). Based on this theoretical approach, enhanced capacity would manifest itself in the number of independent representations that are simultaneously accessible. Thus, transfer of an intervention expanding capacity should be predicted not only to WM tasks, but also to all tasks that demand simultaneous access to multiple separate pieces of information, even without an obvious memory component, such as reasoning tasks (e.g., Halford, Baker, McCredden, & Bain, 2005; Oberauer, Süß, Wilhelm, & Sander, 2007) and attentional tasks (e.g., monitoring tasks, see Oberauer, Süß, Wilhelm, & Wittmann, 2003; Tsubomi, Fukuda, Watanabe, & Vogel, 2013). In contrast, improvements in efficiency would be reflected by more efficiently chunked items (Ericsson & Kintsch, 1995) or faster processing of information. Transfer should be specific to new tasks in which the same chunks, or the same processing operations, can be used again.

So far, the few studies explicitly differentiating between improvements in capacity and efficiency indicate that the latter is more likely to occur. For instance, Wilms, Petersen and Vangkilde et al. (2013) recently evaluated effects of video game training on aspects of cognitive functioning defined within the Theory of Visual Attention (Bundesen, 1990). Their results provided evidence for enhanced visual encoding speed but not for expanded visual WM capacity. Similarly, Salminen, Strobach, and Schubert (2012) found effects of n-back training on attentional tasks (i.e., mixing costs in task switching and T2 identification in an attentional blink paradigm), but not on a reasoning task, indicating that training resulted in faster attentional processes rather than expanded WM capacity.

IMPACT OF INTERVENTION-SPECIFIC FEATURES

One problem that arises when trying to draw conclusions about the effectiveness of WM training is that the regimes employed vary widely across existing studies. The most obvious differences exist regarding the training tasks themselves, but there are also large variations in the intensity and duration of training interventions. In addition, more technical aspects could also play a role, for example, the rule by which task difficulty is adapted during training. Finally, although most researchers agree on the importance of the inclusion of active control groups, there is still no consensus about how a control intervention should be designed.

NATURE OF THE TRAINING TASKS

Existing training regimes can be roughly divided into three approaches: regimes employing single paradigms (e.g., dual n-back training), regimes using multiple paradigms that draw on one broader cognitive construct (e.g., short term and WM), and multi-factorial regimes targeting multiple cognitive skills (e.g., WM and executive functions).

SINGLE-PARADIGM REGIMES

A large subset of training studies focuses on the intensive practice of single paradigms, which allows for studying the malleability of relatively specific aspects or functions of WM such as updating or storage and processing. To avoid material-specific effects, some training regimes include several variants of one type of task using different materials such as verbal or visuo-spatial stimuli (e.g., Chein & Morrison, 2010; von Bastian & Oberauer, 2013).

The most widely used training task is the dual n-back, for which Jaeggi and colleagues demonstrated remarkable effects on measures of intelligence (Jaeggi et al., 2008; Jaeggi et al., 2010). In this task, sequences of visual and auditory stimuli are presented simultaneously, and participants have to constantly decide whether the currently present stimulus in each modality matches the one n steps back. Recent attempts to replicate transfer effects of dual n-back training on reasoning were, however, often not successful (Chooi & Thompson, 2012; Redick et al., 2013; Thompson et al., 2013; but see Schweizer, Hampshire, & Dalgleish, 2011 for a successful replication demonstrating transfer to matrix reasoning using an active control group). Similar paradigms that were used in training studies are the more traditional single n-back task (Heinzel et al., 2013; Li et al., 2008), which comprises updating in only one modality, and the running memory paradigm (Dahlin, Stigsdotter Neely, et al., 2008), in which the last four items of lists with varying and unpredictable length have to be recalled. In both studies, near transfer to non-trained WM measures could be established, but far transfer was not assessed. In fact, one study that directly compared single and dual n-back training (Jaeggi, et al., 2010), provided evidence that both n-back variants are of similar effectiveness.

Although the complex span paradigm is a very popular measure for WM capacity (cf. Conway et al., 2005), it is only rarely used in training studies (Chein & Morrison, 2010; Gibson et al., 2013; von Bastian & Oberauer, 2013). In this paradigm, the rapid presentation of memoranda alternates with a second information processing task, often being a choice reaction time task. Only two of the three training studies employing the complex span task measured far transfer, providing somewhat diverging results. Chein & Morrison (2010) presented evidence for effects on Stroop interference (although only on a subgroup of successfully trained participants) and on reading comprehension, but not on reasoning, whereas von Bastian and Oberauer (2013) did not find any effect on Stroop interference, but on reasoning performance. As there were several differences between the studies regarding procedure and tasks used, there are multiple possible reasons for these contradictory results. Thus, future studies are necessary to determine the effectiveness of the complex span paradigm as a training task.

Overall, the paradigms used for WM training clearly differ in multiple respects, for example which aspect of WM capacity they mainly draw on or the type of strategies being potentially employed. In a recent study, we therefore compared effects of three training interventions each focusing on one specific functional category of WM capacity. In comparison to an active control group, our results indicated larger transfer effects to novel WM and reasoning tasks following complex span (i.e., storage and processing) training than did practicing other WM tasks requiring either relational-integration or executive control (“supervision”) (von Bastian & Oberauer, 2013). In a next step, we plan to explore which functional WM processes underlie the transfer effects observed from storage-and-processing training. Similarly, little is known about the potential domain specificity of WM training interventions, although a meta-analysis indicates that visuo-spatial WM training might lead to more persistent training and near transfer gains than training verbal WM does (Melby-Lervåg & Hulme, 2013). Additional evidence for domain-specific transfer effects comes from a recent study that found transfer effects to matrix reasoning for visuo-spatial, but not for auditory n-back training (Stephenson & Halpern, 2013). It remains unclear, however, whether this effect was due to the nature of the matrix reasoning tasks—which heavily draw on visuo-spatial abilities—or could hold for non-matrix reasoning tasks as well.

MULTI-PARADIGM REGIMES

Instead of using only one specific paradigm, in particular commercially available WM training interventions often comprise a more diverse set of different types of tasks. Such increased variability does not only provide variety to keep trainees’ motivation high, but might actually foster transfer effects as the cognitive process targeted is practiced in different contexts (cf. Schmidt & Bjork, 1992). The probably most thoroughly investigated training intervention “Cogmed” (e.g., Brehmer et al., 2012; 2013; Gibson et al., 2012; Klingberg et al., 2005; McNab et al., 2009) as well as the somewhat less well-known “CogniFit” (e.g., Shiran & Breznitz, 2011) comprise a mix of some WM and mainly short-term memory (STM) tasks. The obvious disadvantage of this approach is that it is unclear whether training STM truly targets WM capacity, because one could question whether STM and WM are identical systems (cf. Shipstead, Hicks et al. 2012; Shipstead, Redick et al., 2012). It has been argued that STM tasks reflect mainly primary (short-term) memory, whereas WM tasks, in particular complex span tasks, draw to a large extent on secondary (long-term) memory (Unsworth & Engle, 2007). In relation to this criticism, Gibson and colleagues directly compared the effectiveness of simple and complex span paradigms regarding their potential to enhance both primary and secondary memory in a series of recent training studies (Gibson et al., 2012, 2013). The results indicated that simple span tasks can be as effective as complex span tasks in targeting both primary and secondary memory. However, these studies included only small samples and did not assess far transfer. Hence, more evidence has to be accumulated to overcome these objections towards training interventions mixing WM and STM paradigms.

MULTI-FACTORIAL REGIMES

Based on the idea that transfer is induced by an overlap of processes required for both training and transfer tasks, interventions targeting multiple cognitive skills could lead to broader transfer effects than single-skill interventions do. Therefore, a third stream of training regimes uses multiple heterogeneous tasks drawing on a variety of cognitive abilities such as WM and executive functions (Jausovec & Jausovec, 2012; Owen et al., 2010; Schmiedek et al., 2010; von Bastian et al., 2013). Indeed, particularly the COGITO training study (Schmiedek et al., 2010), which included the practice of WM, episodic memory, and speed, revealed impressive transfer effects which were even present on the latent level of cognitive abilities. However, other training regimes employing a broad set of tasks were less successful (Owen et al., 2010). So far, to our knowledge, there are no published studies directly testing the hypothesis that multi-factorial training is more effective than single-factorial training. Comparison between two studies from our laboratory suggests that training interventions focusing on the intensive practice of one aspect of WM (i.e., simultaneous storage and processing) are possibly more effective than practice of multiple aspects (i.e., a mixture of storage–processing tasks, relational-integration tasks, and task-switching paradigms) (von Bastian, Langer et al., 2013).

INTENSITY AND DURATION

Another feature in which training regimes often differ concerns training intensity and duration. For example, the number of training sessions completed ranges from only 3 (Borella et al., 2010) to more than 100 sessions (Schmiedek et al., 2010), and the duration of single training sessions varies between only 10 min (Owen et al., 2010) and 30–45 min (e.g., Klingberg et al., 2005; von Bastian & Oberauer, 2013). Most published training regimes comprise around 20 training sessions each lasting about 30?min, but only little systematic research investigated the optimal intensity and duration of WM training interventions. In their first study on dual n-back training, Jaeggi et al. (2008) reported dose-dependent effects of training, with more sessions leading to larger transfer effects. Similarly, Alloway, Bibile and Lau (2013) found that high-dosage training (i.e., 24 sessions within 8 weeks), but not low-dosage training (i.e., 8 sessions within 8 weeks) led to transfer effects of WM training in children with learning difficulties. These findings are corroborated by the fact that the only WM training study so far demonstrating broad far transfer effects on the level of latent factors (Schmiedek et al., 2010) comprised around 100 training sessions.

Also only little is known about optimal scheduling of WM training sessions. Prior research on knowledge and skill acquisition suggests that distributed or spaced practice is more effective than massed practice (e.g., Glenberg &

Lehmann, 1980; Mumford, Constanza, Baughman, Threlfall, & Fleishman, 1994). Recent evidence indicates that this principle might also be true for practicing fluid (i.e., WM) instead of crystalline content. In their study, Penner et al. (2012) compared a schedule of 16 sessions distributed over 4 weeks with a schedule of the same number of sessions but distributed over 8 weeks. The latter group outperformed both a passive control group and the massed-practice group in several non-practiced measures of WM, STM, and mental speed.

ADJUSTMENT OF TASK DIFFICULTY

The vast majority of WM training studies utilizes adaptive training algorithms that adjust the level of task difficulty stepwise to individual performance (for studies using non-adaptive procedures, see Li et al., 2008; Schmiedek et al., 2010). For example, if an individual recalled 80 % correctly in a complex span task, task difficulty can be increased by expanding the list of memoranda that have to be recalled. Similarly, if an individual scores 60 % or less correct task difficulty can be decreased by reducing the list length (cf. von Bastian, Locher, & Ruflin, 2013). The idea behind such procedures is to keep the task challenging throughout the training phase and thereby maximizing WM performance gains. This rationale is driven by the assumption that plasticity is induced if there is a “prolonged mismatch between functional organismic supplies and environmental demands” (Lövden et al., 2010, p. 659). Supporting evidence stems from studies comparing adaptive training to a condition where tasks are practiced on the easiest level of difficulty only (e.g., Brehmer et al., 2012; Holmes, et al. 2009; Klingberg et al., 2005). These studies, however, confound adaptivity and mean level of task difficulty, because the non-adaptive control groups received on average much easier tasks. Therefore, in a study we recently conducted, adaptive training was directly compared to a condition in which the level of task difficulty was varied randomly (von Bastian & Eschen, 2013). Surprisingly, preliminary results show no differences in training or transfer gains between the two types of training procedures in comparison to an active control group. These findings indicate that adaptivity might not play such an important role for the effectiveness of training regimes after all.

ACTIVE CONTROL TRAINING

To evaluate training and transfer effects specific to WM training, experimental groups have to be compared to a second group, which could be a passive (or waiting) or an active control group completing an alternative intervention demanding only little WM. Whereas passive as well as active control groups control for mere retest effects potentially arising from pre-/post-designs, an active control group additionally controls for generic intervention effects (e.g., effects of sticking to a regular training schedule or effects of using a computer) and expectancy effects (Oken et al., 2008). To control for the latter, participants should perceive the alternative intervention as a believable and potentially effective cognitive training. Ideally, training conditions for the different groups should be as similar as possible to control for motivational and psychological effects such as the Hawthorne effect, which refers to improvements in performance due to increased attention to the participants’ behavior (e.g., McCarney et al., 2007).

A growing number of WM training studies now include an active control group, but there is yet no consensus about the optimal design for the alternative intervention. One option is that the active control group practices the experimental training tasks on a constantly low level of difficulty (e.g., Brehmer et al., 2012; Holmes et al., 2009; Klingberg et al., 2005). In this setting, the active control group is exposed to the same stimulus material and task instruction as the experimental group. However, the lack of an adaptive paradigm—and thus the lack of possible motivational boosts from experiencing level-ups and the associated feedback about improving in the training task—means that participants in the control group potentially suffer from a lower level of motivation at the post-test compared to participants in the adaptive training condition (cf. Shipstead, Hicks et al., 2012). Another option is to administer an adaptive alternative intervention comprising tasks that share only little variance with WM capacity, for example, visual matching tasks (e.g., von Bastian & Oberauer, 2013), reading interventions (e.g., Shiran & Breznitz, 2011), or trivia quizzes (e.g., Anguera et al., 2012; Owen et al., 2010; von Bastian, Langer et al., 2013). The advantage of this approach is that the difficulty level and the adaptive nature of the training can be kept equivalent across groups. Nevertheless, two problems hypothetically arise with keeping these features constant but varying the training tasks. First, completing alternative tasks such as trivia quizzes is arguably more enjoyable than completing traditional WM capacity paradigms such as a complex span task. Hence, participants in the control group are potentially more motivated than those in the experimental group. Second, it is still unclear which set of tasks really suits the requirement of demanding only little WM. For example, practicing visual matching tasks leads to massive improvements in speed on these simple decision tasks, and processing speed is in turn strongly correlated with WM capacity tasks (Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007). Consequently, comparing WM and visual matching training could actually result in an underestimation of transfer effects (cf., von Bastian & Oberauer, 2013). Similarly, multiple-choice trivia questions possibly invoke reasoning strategies such as rejection of implausible options; these reasoning processes might require a certain degree of relational integration (i.e., coordinating pieces of information, integrating them into novel structures, and deriving conclusions from them)—an aspect of WM capacity highly related to fluid intelligence (Oberauer et al., 2003, 2008). In sum, whereas the inclusion of non-adaptive control groups bears the risk of overestimating WM training and transfer effects, the usage of adaptive alternative interventions potentially leads to an underestimation of WM training and transfer effects. Therefore, the latter is the more conservative approach, so that positive transfer effects of training are more convincing when obtained against an active control group with a cognitively challenging and engaging alternative intervention. Conversely, active control groups engaged in low-intensity, non-adaptive activities are less conservative, rendering demonstrations of no transfer more convincing.

IMPACT OF INDIVIDUAL DIFFERENCES ON TRAINING AND TRANSFER EFFECTS

The effectiveness of WM training interventions is usually evaluated at the group level, but large individual differences in training and transfer gains show that some individuals benefit more from training than others. Evidence accumulated in past research indicates that several differential factors—such as age, initial cognitive ability or deficits, genetic predispositions, motivational aspects or personality traits—are associated with the magnitude of training and transfer gains.

AGE AND INITIAL COGNITIVE ABILITY

The most thoroughly investigated differential factor associated with WM training and transfer gains is age. Most age-comparative WM training studies report larger training-induced improvements in younger than in older adults (Brehmer et al., 2012; Dahlin, Nyberg et al., 2008; Dorbath et al., 2011; Heinzel et al., 2013; Schmiedek et al., 2010; Zinke et al., 2013; but see Li et al., 2008; von Bastian, Langer et al., 2013). As fluid abilities such as WM and reasoning decline with age (Craik & Bialystok, 2006; Kramer & Willis, 2002; Park et al., 2002), these findings are sometimes interpreted as evidence for a so-called Matthew effect known from educational (e.g., Bakermans-Kranenburg, van IJzendoorn, & Bradley, 2005) and reading research (e.g., Shaywitz et al., 1995; Stanovich, 1986). The Matthew effect—the label of which originates from the Biblical statement “Whoever has will be given more, and they will have an abundance” (Matthew 13:12, New International Version)—refers to cumulative advantages (also referred to as magnification or amplification effects, cf. Kliegl, Smith, & Baltes, 1990; Lövden, Brehmer, Li, & Lindenberger, 2012; Verhaeghen & Marcoen, 1996), which means that individuals with high initial ability are more likely to improve their abilities to an even greater extent. However, recent meta-analyses reported trends that younger children also benefit more from training than older ones (Melby-Lervåg & Hulme, 2013; Wass, Scerif, &

Johnson, 2012). This suggests a linear relationship between age and training gains instead of the inverted-U-shaped function observed for cognitive performance in relation to age. Thus, age effects on training outcomes probably reflect rather a general decline of brain plasticity over the life-span than a sole effect of initial cognitive ability.

Therefore, to examine the impact of a possibly existing Matthew effect on WM training outcomes, age and initial cognitive performance have to be deconfounded. Unfortunately, only very few studies reported whether initial performance alone predicted training and transfer gains. Such a study examining age-independent effects of initial cognitive status was carried out by Yesavage, Sheikh, Friedman, and Tanke (1990). Elderly participants (age range 55–87 years) were taught in mnemonic strategies for two learning tasks (face-name associations and list-learning). Analyses showed that individuals with higher mental status in terms of their scores in the Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975) experienced larger training improvements in list-learning. Importantly, this effect was independent of the additional effect of age on training gains. However, only age but not MMSE score explained individual differences in practice effects in the face-name association task. Notwithstanding these findings, one could argue that explicit strategy training already requires a certain minimal level of cognitive ability, whereas recent approaches to WM training do not rely on explicit learning (cf. Klingberg, 2010) and thus might be differently affected by initial cognitive ability. Indeed, in their dual n-back training study in which no strategies were introduced, Jaeggi et al. (2008) reported findings opposite to a Matthew effect. Transfer effects from dual n-back training on reasoning were larger for those individuals with poorer matrix reasoning scores at pre-test. This result suggests a compensatory effect of training, such that individuals with more room for gains show larger improvements. Similarly, Karbach (2008; see also Karbach & Kray, 2009) showed that lower pre-test scores in switch tasks subsequently practiced were the best predictor for both higher training and higher transfer gains. Despite their study comprising several age groups (children, young adults, and old adults), age did not explain any additional variance in training and transfer gains. These findings were corroborated by Zinke et al. (2013), who found larger training gains for individuals with lower baseline performance. Training gain, in turn, predicted the magnitude of transfer gains in some of their transfer measures (see also von Bastian & Oberauer, 2013).

WM training studies on clinical samples such as individuals with ADHD (e.g., Holmes et al., 2010; Klingberg et al. 2002, 2005), acquired brain injury (Lundqvist, Grundström, Samuelsson, & Rönnberg, 2010), stroke (Westerberg et al., 2007), or problematic drinking behavior (Houben, Wiers, & Jansen, 2011) tend to sometimes observe more transfer than studies on healthy young adults (Wass et al., 2012). This fact also favors the existence of compensatory effects over Matthew effects. However, more evidence is needed before strong conclusions can be drawn about the role of initial cognitive ability in predicting training and transfer gains. Therefore, it would be highly desirable if authors of future WM training studies also report this aspect of the data.

GENETIC PREDISPOSITIONS

Based on twin studies, the heritability of WM capacity is estimated to about 50 % (Ando, Ono, & Wright, 2001; Blokland et al., 2011; Wright et al., 2001). Friedman et al.'s study on the heritability of executive functions even suggests that WM updating is almost entirely genetically determined (Friedman et al., 2008). Dopamine-relevant genes appear to be particularly strongly linked to WM performance (for a review, see Bäckman & Nyberg, 2013). Evidence—although based on small samples only—that such genetic influences could also contribute to individual differences in WM training outcomes was first reported by Brehmer et al. (2009). Based on the genotype of the dopamine transporter gene DAT1, they split a sample of young adults that completed Cogmed WM training into carriers of the DAT1 9/10-repeat allele and carriers of the DAT1 10-repeat allele. As the 10-repeat allele leads to increased gene expression (Heinz et al., 2000; VanNess, Owens, & Kilts, 2005) and thus to a higher level of dopamine reuptake, carriers of the DAT1 10-repeat have fewer active dopaminergic pathways available (cf., Swanson et al., 2000). Despite the absence of between-group differences in initial cognitive performance, carriers of the DAT1 9/10-repeat tended to benefit more from training than carriers of the DAT1 10-repeat, as was indicated by a steeper slope of the averaged training curve. Transfer effects were not assessed in that study.

In addition, Bellander et al. (2011) genotyped the same participants for allelic variations in the LIM homeobox transcription factor 1 alpha (LMX1A), which is another genetic factor contributing to the availability of dopamine (Friling et al., 2009; Nakatani, Kumai, Mizuhara, Minaki, & Ono, 2010) and, hence, potentially affects WM training gains. Of particular interest were three single nucleotide polymorphisms (SNPs) that were previously identified as being associated with the development of Parkinson's disease and which therefore presumably influence the number of dopamine neurons in the midbrain (Bergman et al., 2009). One SNP had to be excluded from the analyses as there was too little variation in genotype in the sample, but for one of the two remaining SNPs, Colzato, van Muijden, Band and Hommel (2011) found a significant effect on verbal (but not on visuo-spatial) WM training gain. Taken together, Brehmer et al.'s (2009) and Bellander et al.'s (2011) findings suggest that genetic predispositions linked to the availability of dopamine could affect WM training-related benefits. As the sample sizes were very small (with subgroups of only 9–18 participants), large-scale replications with more statistical power are strongly needed.

Besides dopamine, the brain-derived neurotrophic factor (BDNF) involved in hippocampal plasticity (Lu & Gottschalk, 2000) possibly plays a role for individual differences in WM training. Of particular interest is the SNP Val66Met, as in comparison to Val homozygotes, carriers of the Met allele were shown to perform poorer in memory tasks (Egan et al., 2003; Hariri et al., 2003), and to have reduced hippocampal volume (Bueller et al., 2006). In a training study with elderly participants, Colzato et al. (2011) compared Val/Val homozygotes with carriers of the Met allele. Although the groups showed similar improvements during the training intervention, only Val/Val homozygous individuals but not Met carriers showed transfer to a divided attention task.

In summary, these first studies provide evidence for genetic predispositions underlying—at least to some extent—individual differences often observed in WM training research. Studies including data on genetic factors are therefore not only very useful for designing individually effective training interventions, but also for exploring the mechanisms of transfer.

MOTIVATION AND PERSONALITY TRAITS

In past research, motivational variables such as interest have been shown to predict cognitive performance (e.g., Hidi, 2006). Brose, Schmiedek, Lövden, Molenaar and Lindenberger (2010) examined the intra-individual covariation of intrinsic motivation (i.e., effort and enjoyment) and WM performance across multiple measurements. For this purpose, they analyzed the data from the COGITO training study (see also Schmiedek et al., 2010) which comprises motivational and WM measures of younger and older adults (each n > 100) across 100 sessions. Results revealed positive day-to-day associations between intrinsic motivation and WM in younger adults, which were reduced in the elderly sample. A recent meta-analytic study investigated the causal direction of such motivational effects by manipulating test motivation and measuring effects on performance in intelligence tests (Duckworth, Quinn, Lynam, Loeber, & Stouthamer-Loeber, 2011). They demonstrated that when motivation is enhanced through material incentive, scores in intelligence tests were increased on average by 0.64 standard deviations, with initially lower scoring individuals showing larger effects of the manipulation. This again underlines the necessity of learning more about optimal active control interventions. If the alternative intervention is more or less rewarding for participants than the WM training—either because of different levels of boredom and perceived effort, or because of different degrees of perceived success—the two groups are likely to differ in motivation on the transfer tasks, thereby biasing the comparison between training and control group.

Besides motivation, personality traits such as neuroticism and conscientiousness could possibly interact with intervention-specific features and thereby affect WM training and transfer gains. Matching earlier findings that anxiety impairs cognitive performance (for a review, see Derakshan & Eysenck, 2009) and training outcomes (Yesavage & Jacob, 1984), Studer-Luethi, Jaeggi, Buschkuehl and Perrig (2012) found that higher scores in neuroticism were negatively associated with training gain. For conscientiousness, results indicated that highly conscientious individuals showed larger training gains. Improvements in matrix reasoning were, however, smaller for these participants. The authors explain these results by individuals scoring high in conscientiousness possibly having developed task-specific strategies that were useful for the training tasks, but might have counteracted enhancements in capacity and, hence, impaired transfer gains. However, in a recent replication attempt, Thompson et al. (2013) could not confirm associations between conscientiousness and training gain. Furthermore, higher conscientiousness scores were related to smaller improvements only in matrix reasoning measured by Raven's Advanced Progressive Matrices (Raven, 1990), but not to any other indicator of fluid intelligence. In evaluating these results, it is important to bear in mind that the sample sizes in both studies were uncomfortably small for correlational analyses, with n = 20 in Thompson et al.'s study (2013), and n =46 in Studer-Luethi et al.'s (2012) study. Therefore, the result patterns first have to be replicated in larger samples before being interpreted substantively.

Taken together, motivational states and traits as well as personality traits potentially contribute to between-person variability in WM training and transfer effects. Research revealed positive associations between cognitive performance and motivation, and changes in specific motivational mindsets could potentially mimic or obscure existing effects. To broaden the understanding of such effects, it would be helpful to include measures such as the Intrinsic Motivation Inventory (Deci & Ryan, 2013; Ryan & Deci, 2000). The existing picture is much less clear for personality traits, as the few correlational patterns reported are quite inconsistent. Studies including larger samples are crucial to learn more about the influence of these personality factors. Deeper knowledge about the personality factors impacting effects of WM training could especially help design tailor-made approaches that maximize effects at an individual level.

CONCLUSION

Although it might appear that an exploding number of training studies is published at the moment, still only very little is known about the mechanisms of transfer and factors potentially impacting these mechanisms. We suggest two possible mechanisms that could underlie the transfer effects occasionally observed: increased WM capacity or enhanced WM efficiency. So far, it is hard to say whether WM training interventions were successful in increasing WM capacity, as transfer was often evaluated with single tasks and outside of theoretical frameworks distinguishing between capacity and efficiency. To answer the question "Can WM be improved?", we therefore think that future studies should be designed within such theoretical frameworks, and a priori predictions should be made about the nature of possible effects of WM training. Furthermore, as results of past studies are very inconsistent if not contradictory, the more appropriate question to ask about WM training is perhaps "Under which circumstances, and for which person, can WM be improved and why?" To get closer to answer this question, we summarized findings concerning on the one hand intervention-specific features such as the training regime and conditions, and on the other hand individual differences potentially impacting WM training outcomes such as initial cognitive ability, genetic predispositions, and motivation and personality (summarized in Table 1). By doing so, we found that there is still a lot of work to do to fill the existing wide gaps with empirical evidence before we can conclude whether and under which circumstances WM training can improve cognitive performance beyond task-specific practice effects.

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Table 1

Categorization of Working Memory Training Studies Included in the Review.

Author (year)	**Type of Regime (* adaptive)**	**Type of Control Group**	**Reports Effects of intervention-specific features**	**Population**	**Reports Effects of Age or Initial Ability**	**Reports Biological Correlates**	**Reports Effects of Motivation or Personality**	**Assessed Near Transfer**	**Assessed Far Transfer**
Chein & Morrison (2010)	SP* (complex span)	passive	-	YA	-	-	-	Yes	Yes
Richmond et al. (2011)	SP* (complex span)	non-adaptive + (trivia)	-	OA	-	-	-	Yes	Yes
von Bastian & Oberauer (2013)	SP* (3 groups: complex span, relational integration, task switching)	adaptive (perceptual matching)	-	YA	-	-	-	Yes	Yes
Dorbath et al. (2011)	SP (continous counting)	none	-	YA OA	age	-	-	No	No
Jaeggi et al. (2008)	SP* (dual n-back)	passive	dosage	YA	initial ability	-	-	Yes	Yes
Jaeggi et al. (2010)	SP* (dual n-back)	passive	-	YA	-	-	neuroticism and conscientiousness (reported in Studer-Luethi et al., 2010)	Yes	Yes

Lilienthal et al. (2013)	SP* (dual n-back)	passive and non-adaptive	-	YA	-	-	-	Yes	No
Redick et al. (2013)	SP* (dual n-back)	adaptive (visual search)	-	YA	-	-	-	Yes	Yes
Salminen et al. (2012)	SP* (dual n-back)	passive	-	YA	-	-	-	Yes	Yes
Schweizer et al. (2011)	SP* (dual n-back)	adaptive (feature matching)	-	YA	-	-	-	Yes	Yes
Stephenson & Halpern (2013)	SP* (dual n-back)	passive and adaptive (spatial STM)	-	YA	-	-	-	No	Yes
Thompson et al. (2013)	SP* (dual n-back)	passive and adaptive (multiple object tracking)	-	YA	-	-	conscientiousness, self-rated grit, and growth mindset	Yes	Yes
Anguera et al. (2012)	SP* (dual-n-back)	non-adaptive + (knowledge trainer)	-	YA	-	-	motivation during intervention	Yes	Yes
Chooi & Thompson (2012)	SP* (dual-n-back)	passive and non-adaptive	dosage	YA	-	-	-	Yes	Yes
Dahlin, Nyberg, et al. (2008)	SP* (memory updating)	passive	-	YA OA	age	-	-	Yes	Yes
Dahlin, Stigsdotter	SP* (memory updating)	passive	-	YA	age	functional	-	Yes	Yes

Neely, et al. (2008)				OA					
Oberauer (2006)	SP (memory updating)	none	-	YA	-	-	-	No	No
Verhaeghen et al. (2004)	SP (memory updating)	none	-	YA	-	-	-	No	No
Heinzel et al. (in press)	SP* (n-back)	passive	-	YA OA	age	-	-	Yes	Yes
Li et al. (2008)	SP (n-back)	passive	-	YA OA	age	-	-	Yes	No
Karbach & Kray (2009)	SP (task-switching)	non-adaptive + (choice reaction time tasks without switching)	-	CH YA OA	age and initial ability (cf. Karbach, 2008)	-	-	Yes	Yes
Penner et al. (2012)	MP* (BrainStim)	passive	scheduling	MA	-	-	-	Yes	Yes
Bellander et al. (2011)	MP* (Cogmed)	none	-	YA	-	genetic	-	No	No
Brehmer et al. (2009)	MP* (Cogmed)	none	-	YA	-	genetic	-	No	No
Brehmer et al. (2012)	MP* (Cogmed)	non-adaptive	-	YA OA	age	-	-	Yes	Yes
Gibson et al. (2012)	MP* (Cogmed)	none	-	YA	-	-	-	Yes	No

Gibson et al. (2013)	MP* (Cogmed)	passive	accuracy threshold for adaptive algorithm	YA	-	-	-	Yes	No
Holmes et al. (2009)	MP* (Cogmed)	non-adaptive	-	CH (low WM)	-	-	-	Yes	Yes
Holmes et al. (2010)	MP* (Cogmed)	none	-	CH (ADHD)	-	-	-	Yes	Yes
Houben et al. (2011)	MP* (Cogmed adaptation)	non-adaptive	-	A (heavy drinkers)	-	clinical	-	No	Yes
Klingberg et al. (2002), Study 1	MP* (Cogmed)	non-adaptive	-	CH (ADHD)	-	clinical	-	Yes	Yes
Klingberg et al. (2002), Study 2	MP* (Cogmed)	non-adaptive (from Study 1)	-	YA	-	-	-	Yes	Yes
Klingberg et al. (2005)	MP* (Cogmed)	non-adaptive	-	CH (ADHD)	-	clinical	-	Yes	Yes
Lundqvist et al. (2010)	MP* (Cogmed)	passive	-	A (acquired brain injury)	-	clinical	-	Yes	Yes
McNab et al. (2009)	MP* (Cogmed)	none	-	YA	-	biochemical	-	Yes	No
Olesen et al. (2004)	MP* (Cogmed)	passive	-	YA	-	functional	-	Yes	Yes
Westerberg et al. (2007)	MP* (Cogmed)	passive	-	A (stroke)	-	clinical	-	Yes	Yes
Shiran & Breznitz (2011)	MP* (CogniFit)	non-adaptive + (reading)	-	YA (dyslexic students	-	clinical	-	Yes	Yes

				and skilled readers)					
Alloway & Bibile (2013)	MP* (Jungle Memory)	passive	dosage	CH (learning difficulties)	-	-	-	Yes	Yes
Borella et al. (2010)	MP(*) (WM tasks)	non-adaptive + (questionnaires)	-	OA	-	-	-	Yes	Yes
Jausovec & Jausovec (2012)	MP* (WM tasks)	non-adaptive + (communication training)	-	YA	-	functional	-	Yes	Yes
Zinke et al. (in press)	MP* (WM tasks)	passive	-	YA OA	age and initial ability	-	-	Yes	Yes
Owen et al. (2010)	MF (attention, memory, mathematics, and visuospatial processing)	non-adaptive + (knowledge questions)	-	A	-	-	-	Yes	Yes
Colzato et al. (2011)	MF* (EF and WM)	non-adaptive + (documentaries)	-	OA	-	genetic	-	No	Yes
von Bastian et al. (2013)	MF* (EF and WM)	adaptive (trivia, visual search, and counting)	-	YA OA	age	functional (reported in Langer et al., in press)	-	Yes	Yes
Schmiedek et al. (2010)	MF (episodic memory, speed, WM)	passive	-	YA OA	-	-	variability in motivation during training phase (reported in	Yes	Yes

	Brose et al., 2010)

Note. Near transfer tasks were defined as tasks measuring the trained tasks (irrespective of task material or surface characteristics), whereas far transfer tasks were defined as tasks measuring other cognitive abilities than the trained ones. * = adaptive training regime, (*) = partly adaptive training regime. CH = children, YA = young adults, MA = middle-aged adults, OA = older adults, A = adults (no specific age range). SP = single-paradigm regime, MP = multiple-paradigms regime, MF = multiple-factors regime.