Limitations and chances of working memory training

Daniela Nussbaumer (nussbaumer@ifv.gess.ethz.ch)
Institute for Behavioral Sciences, ETH Zurich, Universitätsstrasse 41
8092 Zurich, Switzerland

Roland H. Grabner (roland.grabner@psych.uni-goettingen.de)
Department of Psychology, Georg-August-University of Göttingen, Waldweg 26
37073 Göttingen, Germany

Michael Schneider (m.schneider@uni-trier.de)
Department of Psychology, University of Trier, Universitätsring 15
54296 Trier, Germany

Elsbeth Stern (stern@ifv.gess.ethz.ch)
Institute for Behavioral Sciences, ETH Zurich, Universitätsstrasse 41
8092 Zurich, Switzerland

Abstract

Recent studies show controversial results on the trainability of working memory (WM) capacity being a limiting factor of human cognition. In order to contribute to this open question we investigated if participants improve in trained tasks and whether gains generalize to untrained WM tasks, mathematical problem solving and intelligence tests.

83 adults trained over a three week period (7.5 hours total) in one of the following conditions: A high, a medium or a low WM load group. The present findings show that task specific characteristics could be learned but that there was no transfer between trained and untrained tasks which had no common elements. Positive transfer occurred between two tasks focusing on inhibitory processes. It might be possible to enhance this specific component of WM but not WM capacity as such. A possible enhancement in a learning test is of high educational interest and worthwhile to be investigated further.

Keywords: working memory; training; intelligence; inhibition

Theoretical Background

The concept of WM has received much attention lately by various psychological disciplines for its importance as a basis of human intelligence and as a limiting factor of human cognition. WM can be seen as a cognitive system for simultaneously storing and manipulating information, and hence strongly relates to reasoning abilities and the handling of novel information (Baddeley & Hitch, 1974). Also the attention to goal-relevant information and inhibition of irrelevant information are important functions of WM.

High correlations between WM capacity and intelligence (Oberauer, Süss, Wilhelm, & Wittmann, 2008), notably when measured by Matrices Tests (e.g. Advanced Progressive Matrices Test; Raven, 1990) as well as high correlations between WM capacity and applied fields, e.g. mathematical problem solving tasks leave the following open question: What happens to intelligence and mathematical problem solving skills when WM capacity potentially gets enhanced? One possibility could be a likewise enhancement of WM and intelligence (and mathematical problem solving skills). The similarity of the two concepts would make far transfer plausible. But as stated earlier, results are controversial and more evidence is needed.

Early studies were positive in judging the possibility of a WM training being able to enhance WM capacity and performance in related fields. These early studies were also more explorative in nature. Later studies took criticism (Moody, 2009; Sternberg, 2008) into consideration and the complexity of study designs has been raised (for example by Redick et al. (2012) a non-replication of the study by Jaeggi, Buschkuehl, Jonides, & Perrig, (2008)). In the current study the following criticisms of the past studies are taken into consideration and examined: a) inclusion of an active control group, b) administering a wide variety of transfer tasks and c) examining long term effects.

The trainability of WM capacity would mean that we are able to broaden an important limiting factor of human cognition and this would be of highly practical as well as of seminal educational relevance. There is a growing body of WM training literature (Chein & Morrison, 2010; Klingberg, 2010; Shipstead, Redick, & Engle, 2012). Melby-Lervåg and Hulme (2012) conducted a meta-analytic study and compared effects: Across training studies, effects vary in whether WM training paradigms are effective in improving cognitive abilities.

We included three training groups: a high, a medium and a high WM load group. Their training differed in the amount as well as in the type of WM load included. The first two groups focused on resolution of proactive interference – an ability tapping the WM subcomponent of inhibition, which is regarded as critical subcomponent of WM (Friedman & Miyake, 2004). The third group was an active control group (low to zero WM load) solving a control reaction time task. The further manipulations referred to whether the task was adaptive and whether the task was dual. If WM load during training is the crucial factor for transfer effects to occur there should of course be no training gains for control groups and gains should be more pronounced for a high than for a medium WM load group. The advantage of a graded design lies in being able to differentiate whether a transfer gain can be attributed to enhanced WM capacity or not.

The inclusion of a wide variety of transfer tasks is necessary to decide whether changes can be attributed to an enhancement of WM capacity or merely to task specific learning because an enhancement of WM capacity can only be demonstrated if transfer occurs generally and is not limited to single tasks (Shipstead et al., 2012). In the present study transfer to an untrained WM task is referred to as near transfer and transfer to tasks with another cognitive demand than WM is categorized as far transfer. Far transfer is typically measured using intelligence tests as well as other reasoning tests. In addition to intelligence tests, in the present study mathematical tasks are administered to assess possible far transfer to school-related abilities. According to a literature review by Raghubar, Barnes, and Hecht (2010), WM and skills in mathematical problem solving are highly correlated, in particular mental arithmetic, and are therefore suitable as transfer tasks.

In sum, the main goal of the current study is to test a) whether a WM training yields near transfer, an enhancement of performance in untrained WM tasks, and b) to systematically test whether such a potential WM enhancement can provoke far transfer in the domain of intelligence and mathematical problem solving and whether such an enhancement is depending on the amount of WM load during training. Further we investigate to what extent training gains are found in an active control group, to what extent enhancement of performance is dependent on to the level of WM load during training and how stable these effects are.

Method

Participants

A total of 83 healthy students of science- and humanities-related fields from three Swiss universities completed the study (M_{age} = 23.7, SD = 3.3).Eight participants dropped out due to installation problems of the training software on their home computer (5 participants) or due to non-adherence to the training paradigms or sessions at the institute (3 participants).

Procedure

Participants were randomly designed to one of three groups: A high, a medium or a low WM load group. All groups trained during a three week period five days a week for half an hour on their home computer, resulting in a total training time of 7.5 hours. The first and the last training session were completed at the institute in order to ensure understanding of the tasks and to control for the correct handling of the training software. Solution rates and times as well as other parameters were logged by the training software for all sessions. Before and after training, two assessment sessions took place at the first author's institute: An individual and a group session where participants had to solve WM tasks and a mental arithmetic task, mathematical problem solving tasks and intelligence tests. The sessions before training served to assess baseline performance and the sessions after training aimed to assess possible transfer from the WM training. In order to make an intervention and a possible enhancement meaningful it should show an impact over a certain time. Long term training effects were assessed by a follow-up testing session after a three months period. Participants again solved trained tasks as well as paralleled versions of untrained tasks.

The three groups did not differ significantly in their initial intelligence level, in demographical factors (age, sex, field of study) and in personality factors (measured by the NEO-FFI (Costa & McCrae 1992)). Their initial performance of training and transfer tasks was also in the same range and didn't differ significantly between groups.

Material

Training

A high WM load group trained a dual version of the n-back task, similar to Jaeggi et al. (2008). Simultaneously, letters were presented orally and squares visually at different positions on the screen. Participants had to indicate whether the letter and the position n trials back was the same or not. This adaptive and dual version of the n-back task placed high WM load because a large amount of interference trials was incorporated. Also the duality of the task adds to the high WM load level. Through the dual nature of the task participants trained the visual and oral domain simultaneously. Participants worked on the task for 30 minutes per day with the size of n adapted to the actual level of performance. In this group the average n-back level was assessed.

The medium WM load group trained with three non-adaptive WM tasks: A three-back task with letters and the following two recognition tasks. In the face recognition task participants had to decide whether a single face was part of a previously presented set of four faces or not. In the letter recognition task participants had to decide whether a letter was part of the previously presented set of four letters or not. The tasks were characterized by moderate WM load with a focus on resolution of proactive interference in WM. Solution times and rates were measured and each task was performed for 10 minutes. In all three tasks, a high level of interference was produced by incorporating a large amount of lure trials, i.e., trials in which the objects were shown in another trial than the one actually referred to.

The low WM load group trained similar tasks as the medium WM load group, but with a very low WM load. Participants had to solve a 1-back task and for the recognition tasks participants had to compare one face/letter with a previously presented single face/letter. Solution time and rates were measured.

The amount of WM load is not the only variation between the three groups but all other differences as for example duality vs. singularity of the task can also be seen as a variation of the level of WM load.

Tasks to assess near transfer

The four WM transfer tasks each represented a different subcomponent of WM and showed varying similarities to the trained tasks. In the complex span task participants solved simple equations while keeping single letters in mind. At task switching participants had to either decide whether the value of a three digit number was below or above 500, or whether the number was even or odd. In a monitoring task participants had to detect changes in a grid of nine three-digit-numbers and react on certain constellations of same final digits. A forth WM transfer task was kept very similar to a trained task of the medium WM load group. In this so called 'pseudowords'-task, participants of the medium WM load group had to accomplish the same task requirements as in their trained letter recognition task and also the trained face recognition task was very similar. The mentioned transfer and training tasks showed the same surface structure but other content material than the trained task: Recognition of pseudowords, nonsense syllables obeying phonetic rules, in the transfer situation instead of the trained recognition of single letters or faces. For the control group the same was true except that they trained task versions with minimal WM load. The high WM load group on contrary had no correspondent training.

Tasks to assess far transfer

As fluid intelligence tests the Advanced Progressive Matrices Test (APM, Set II) by Raven (1990) and the 'Intelligenz-Struktur-Test' (I-S-T 2000 R) by Amthauer, Brocke, Liepmann, and Beauducel (2001) were administered.

The three transfer tasks of the mathematical domain consisted of different levels of reasoning requirements and complexity. A mental arithmetic task with subtractions of two digit numbers with carries was conducted without participants taking any notes. A so-called mathematics test (Mathematik-Test, Ibrahimovic & Bulheller, 2005) was exhibited to test participants' ability to solve mathematical word problems. In a last mathematical task with high WM load participants had to keep in mind three simple but interlinked equations as well as the value of the three unknowns.

Learning of novel material

We further investigated whether WM training can enhance the learning of novel material. In this task participants learned to calculate in the septimal system (base 7 system) while inhibiting their usual counting routines of the decimal system. This learning task was presented immediately after the last training session and in order to assess the learning of new principles and the establishing of new routines while overcoming well-trained ones the task comprised of a 40 min problem solving period with a total of 150 trials of additions in the septimal system. This design enables us to investigate the possibility of not only having WM training enhance certain untrained WM tasks, but also enhance the chance of grasping and administering new principles and rules. This would be new and very tempting for educational purposes.

Results

In the medium and high WM load groups the implementation check was positive in that through training participants enhanced their performance significantly in trained tasks. The medium WM load group showed significant increases in solution time and solution rate in the three trained tasks. The high WM load group showed significant increase in the average n-back-level. Participants of the low WM load group also significantly increased their solution times, but not solution rates (see Appendix, Table 1).

Enhancements specific to groups occurred in two of nine untrained tasks. First, group specific enhancements occurred in the 'pseudowords' task. An ANOVA for reaction time measures with the between subject factor group and the within subject factor time was conducted. A significant interaction between time and group ($F(2.99,\ 118.09) = 22.92$, $p < .001$, $\eta^2_p = .37$; see also Figure 1 and Appendix Table 2) and pairwise comparisons revealed that the medium and low WM load groups likewise accelerated more than the high WM load group, which showed only slight enhancement. This analysis also showed a significant main effect time as all participants got faster ($F(1.50,\ 118.09) = 136.18$, $p < .001$, $\eta^2_p = .63$).

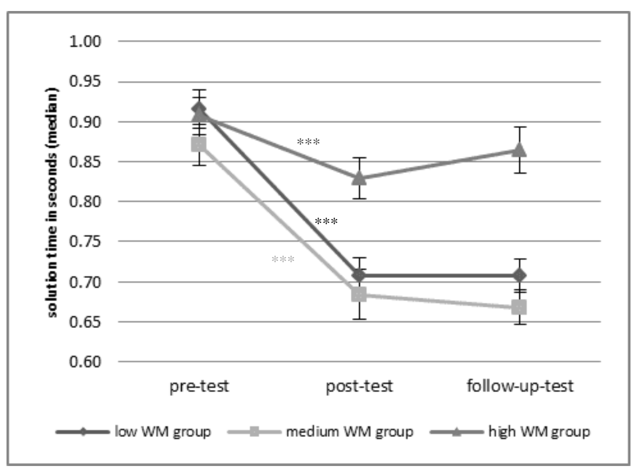

Figure 1: Course of solution times in the transfer task 'pseudowords' during and after training. *** indicate time periods with group specific significant main effects, $p < .001$. Please note, that there is also a significant interaction between time (pre-, post and follow-up-test) and the three groups.

The second differential transfer gain occurred in the one learning task. In the 'Base7' task groups varied in their amount of gain manifesting in a significant interaction between groups and beginning versus end of the test (F(11.19, 447.74) = 2.15, p <.05, η^2_p =.05). Post hoc tests showed that the high WM load group showed a higher degree of progress than the low WM load group over the course of the 150 trials (see Figure 2). In this task all groups enhanced their performance significantly over the 150 trials (F(5.60, 447.74) = 32.67, p <.001, η^2_p =.29).

No differential transfer occurred in any of the mathematical problem solving tasks or in the intelligence tests, therefore in none of the untrained WM tasks such interactions were found. However, there was a significant temporary enhancement of solution times and rates for all transfer tasks, but with no difference between the three groups, as no interaction was detected (see table 2 for changes from pre- to post-measure).

Long term gains over a three month period were found in some tasks, but no differences between the three groups were found. The only exception is the aforementioned recognition task 'pseudowords', where differential changes between pre- and post-tests could be held throughout the three months.

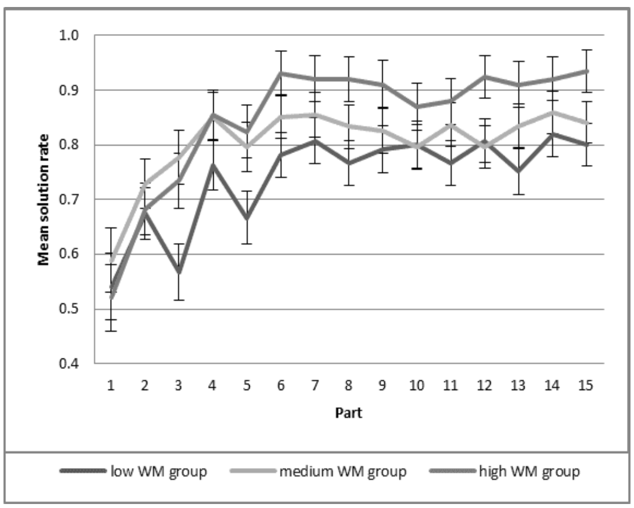

Figure 2: Course of solution rates in the learning task 'Base7'. The y-axis represents solution rate (1.0 = maximum, 0.5 = 50% right). The x-axis marks the 15 parts of the test, 10 trials are summarized into one part. Please note, that there is a significant interaction between part (1-15) and group (low, medium and high WM load).

Discussion

The actual focus of the present study are the questions to what extent training gains are found in an active control group, to what extent enhancement of performance is dependent on to the level of WM load during training, what near and far transfer effects can be observed and how stable these effects are. Only in two out of nine cases were such differential enhancements found. In all other untrained WM tasks no such interactions were found so that no positive transfer specific to medium or high WM load during training occurred in any of the mathematical problem solving tasks or in any intelligence tests. According to Shipstead et al. (2012) it is crucial to compare a wide variety of tasks to decide where the reason of changes may lie. Generally occurring transfer effects could be attributed to an enhancement of WM capacity whereas rare transfer should be explained by only task specific learning. For the present study it can therefore be concluded that no enhancement of WM capacity as such is found.

The two cases of group specific enhancement are discussed separately. First, differential enhancement occurred in one untrained task with a similar surface structure but different content material than in the trained tasks of the medium WM load group (recognition of 'pseudowords' instead of recognition of letters). Also the low WM load group trained a recognition task with the same surface structure but minimal WM load. Both the medium and low WM load group developed similarly, this suggests that high WM load was not essential for the development, but rather the similarity of the trained and untrained task. This explains why the development of the low WM load group was likewise the one of the medium WM load group and why the high WM load group – training with a very different paradigm but being exposed to high WM load during training – developed in a different way. In conclusion, training gains can transfer to very similar tasks only. The similarity of the tasks or in other words the common elements of trained and untrained tasks are crucial for transfer.

Second, in the 'Base7' learning task all groups enhanced their performance significantly over the 150 trials, but the high WM load group showed a higher progress than the low WM load group. The trained dual n-back task of the high WM load group and the 'Base7' task at their surface show no similarity but both tasks particularly focused on inhibitory processes. It can therefore be concluded, that inhibitory processes could possibly be enhanced through a specific training focusing on inhibition. In order to exclusively answer this assumption more evidence would be needed to exclude the possibility of just task specific characteristics being responsible for this result. Moreover, this gain was measured in a novel task type: A learning task – to our knowledge not administered in any other WM training study and the only learning task included in the present WM training study. The possible enhancement in a learning test is of high educational interest and also has to be verified by further testing.

There was significant general enhancement of solution times and solution rates for all transfer tasks, but no difference between the three groups for seven of nine tasks. As also the low WM load group with virtually zero WM load during training got significantly better from pre- to post-test, enhancement cannot be explained by expanded WM capacity. It can therefore be stated that participants perform significantly better after WM training but not due the characteristics of the training and not due to an enhancement of WM capacity.

Numerous authors (Chein & Morrison, 2010; Moody, 2009; Shipstead, Redick, & Engle, 2010; Shipstead et al., 2012; Sternberg, 2008) judge the selection of an appropriate control group as essential in interpreting data. In the present study the low WM load group served as an active control group and also increased their performance. Through an active control group effects due to a different degree of study involvement can be ruled out.

Long term gains over a three month period were found in some tasks, but no differences between the three groups were found. The only exception is the aforementioned recognition task where the differential changes between pre and post testing could be held throughout the three months.

In summary, the theoretical and educational significance of the present results are threefold. First, our results suggest that WM training is of limited use to enhance human cognition in general. The present findings show that task specific characteristics could be learned but that there was no transfer between trained and untrained tasks which had no common elements. Second, as positive transfer occurred between two tasks focusing on inhibitory processes, it might be possible to enhance this specific component of WM. Third, the possible enhancement in a learning test is of high educational interest and is worthwhile to be further investigated.

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Appendix

Table 1: Data for each training task and separately for solution time and rate reporting an ANOVA (within-subject factor time: 13 sessions). Cohen's *d* was derived from comparisons between the first and the last session.

Solution time	**ANOVA: 13 sessions**	**Cohen's *d***
Low WM load group		
1-back	$F(5.83,134.02) = 7.82$ $p < .001$ $\eta^2_p = .25$	$d = -0.80$
1-Face	$F(5.35, 112.24) = 5.108$ p < 0.001 $\eta^2_p = 0.20$	$d = -0.73$
1-Letter	$F(4.54, 104.50) = 10.60$ p < 0.001 $\eta^2_p = 0.32$	$d = -0.91$
Medium WM load group		
3-back	$F(4.57, 109.58) = 13.56$, p < 0.001 $\eta^2_p = 0.36$.	$d = -1.18$
4-Faces	$F(4.31, 103.49) = 20.82$ $p < 0.001$ $\eta^2_p = 0.45$	$d = -1.40$
4-Letters	$F(5.24,125.86) = 11.14$ p < 0.001 $\eta^2_p = 0.32$	$d = -0.84$

Solution rate	**ANOVA: 13 sessions**	**Cohen's *d***
Low WM load group		
1-back	n.s	$d = 0.47$
1-Face	n.s.	$d = -0.32$
1-Letter	n.s.	$D = -0.01$
Medium WM load group		
3-back	$F(2.64, 63.24) = 12.53$ $p < .001$, $\eta^2_p = .34$	$d = 1.33$
4-Faces	$F(12,31) = 2.00$ $p < 0.05$ $\eta^2_p = 0.07$	$d = 0.56$
4-Letters	n.s.	$d = 0.52$
High WM load group		
Dual-N-back	$F(3.63,101.70) = 29.23$ $p < 0.001$ $\eta^2_p = 0.51$	$d = 1.76$

Table 2: Transfer data for each task reporting main and interaction effects for an ANOVA (between-subject factor group: low, medium and high load and within-subject factor time: pre-, post-, and follow-up-testing)

Pre – Post	Main effect time	Main effect group	Interaction time * group
ABC task Solution time	$F(1,80) = 113.49$ $p < 0.001$ $\eta^2_p = 0.59$ $d = -0.83$	n.s. $\eta^2_p = 0.02$	n.s. $\eta^2_p = 0.03$
Pseudo-words Solution time	$F(1,80) = 122.82$ $p < 0.001$ $\eta^2_p = 0.61$ $d = -1.09$	$F(2,80) = 2.12$ $p < 0.05$ $\eta^2_p = 0.10$	$F(2,80) = 6.95$ $p < 0.01$ $\eta^2_p = 0.15$
Task Switch Solution time	$F(1,79) = 136.01$ $p < 0.001$ $\eta^2_p = 0.63$ $d = -0.78$	$F(2,79) = 7.03$ $p < 0.01$ $\eta^2_p = 0.15$	$F(2,79) = 3.31$ $p < 0.05$ $\eta^2_p = 0.08$
Monitor-ing Solution time	$F(1,80) = 28$ $p < 0.001$ $\eta^2_p = 0.26$ $d = -0.68$	n.s. $\eta^2_p = 0.03$	n.s. $\eta^2_p = 0.01$
Mental Arith-metics Solution time	$F(1,79) = 8.78$ $p < 0.01$ $\eta^2_p = 0.10$ $d = -0.24$	n.s. $\eta^2_p = 0.02$	n.s. $\eta^2_p = 0.02$
Operation-Span Solution time	$F(1,80) = 45.62$ $p < 0.001$ $\eta^2_p = 0.36$ $d = -0.52$	n.s. $\eta^2_p = 0.05$	n.s. $\eta^2_p = 0.01$
ABC task Solution rate	$F(1,80) = 4.95$ $p < 0.05$ $\eta^2_p = 0.06$ $d = 0.29$	n.s. $\eta^2_p = 0.04$	n.s. $\eta^2_p = 0.04$
Pseudo-words Solution rate	$F(1,80) = 19.14$ $p < 0.001$ $\eta^2_p = 0.19$ $d = 0.54$	n.s. $\eta^2_p = 0.01$	n.s. $\eta^2_p = 0.03$
Task Switch Solution rate	$F(1,79) = 65.91$, $p < 0.001$ $\eta^2_p = 0.46$ $d = 0.63$	n.s. $\eta^2_p = 0.05$	n.s. $\eta^2_p = 0.00$
Monitor-ing Solution rate	$F(1,80) = 16.27$ $p < 0.001$ $\eta^2_p = 0.17$ $d = 0.48$	n.s. $\eta^2_p = 0.02$	n.s. $\eta^2_p = 0.01$
Mental Arith-metics Solution rate	$F(1,79) = 7.53$ $p < 0.01$ $\eta^2_p = 0.09$ $d = 0.36$	n.s. $\eta^2_p = 0.01$	n.s. $\eta^2_p = 0.04$
Operation-Span Solution rate	$F(1,80) = 25.61$ $p < 0.001$ $\eta^2_p = 0.24$ $d = 0.60$	n.s. $\eta^2_p = 0.02$	n.s. $\eta^2_p = 0.01$
Mathe-matik-Test Solution rate	$F(1,79) = 12.98$ $p = 0.001$ $\eta^2_p = 0.14$ $d = 0.40$	n.s. $\eta^2_p = 0.02$	n.s. $\eta^2_p = 0.03$
I-S-T Solution rate	$F(1,80) = 54.54$ $p < 0.001$ $\eta^2_p = 0.41$ $d = 0.61$	n.s. $\eta^2_p = 0.04$	n.s. $\eta^2_p = 0.01$
APM Solution rate	$F(1,79) = 5.39$ $p < 0.05$ $\eta^2_p = 0.06$ $d = 0.22$	n.s. $\eta^2_p = 0.07$	n.s. $\eta^2_p = 0.05$