The efficacy of working memory training in improving crystallized intelligence

Tracy Packiam Alloway[1] & Ross G. Alloway[2]

[1]Psychology Department, University of Stirling, Stirling FK9 4LA, UK; [2]English Literature Department, University of Edinburgh, Edinburgh EH8 9JZ, UK). These authors contributed equally to this work.

Crystallized intelligence (*Gc*) is thought to reflect skills acquired through knowledge and experience and is related to verbal ability, language development[1] and academic success[2]. *Gc*, together with fluid intelligence (*Gf*), are constructs of general intelligence[3]. While *Gc* involves learning, knowledge and skills, *Gf* refers to our ability in tests of problem-solving, pattern matching, and reasoning. Although there is evidence that *Gf* can be improved through memory training in adults[4], the efficacy of memory training in improving acquired skills, such as *Gc* and academic attainment, has yet to be established. Furthermore, evidence of transfer effects from gains made in the trained tasks is sparse[5]. Here we demonstrate improvements in *Gc* and academic attainment using working memory training. Participants in the Training group displayed superior performance in all measures of cognitive assessments post-training compared to the Control group, who received knowledge-based training. While previous studies have indicated that gains in intelligence are due to improvements in test-taking skills[6], this study demonstrates that it is possible to improve crystallized skills through working memory training. Considering the fundamental importance of *Gc* in acquiring and using knowledge and its predictive power for a large variety of intellectual tasks, these findings may be highly relevant to improving educational outcomes in those who are struggling.

Working memory capacity is thought to be as a fluid cognitive skill[7] that is closely linked with fluid intelligence (*Gf*)[8]. There is substantial evidence that working memory and *Gf* share neural substrates, such as the prefrontal and parietal cortices[9,10]. While some psychologists suggest that the two constructs are so highly correlated that they could be considered as isomorphic properties[11], *Gf* and working memory do appear to be dissociable[12,13]. Given both the neural basis and the psychometric evidence for the close relationship between working memory and *Gf*, training of one neural circuit might led to benefits in another shared domain. Indeed, recent evidence suggests that memory training results in gains in fluid intelligence[4], though this finding is controversial[14].

In contrast to *Gf*, crystallized intelligence (*Gc*) reflects acquired skills and knowledge. Accordingly, different neural substrates are associated with *Gc:* it is more closely linked to brain regions that involve the storage and usage of long-term memories, such as the hippocampus[15]. Would training fluid cognitive skills, such as working memory, result in improvements in acquired skills, such as *Gc* and academic attainment? To assess the potential gains in acquired skills as the result of working memory training, we used a paradigm to train working memory in the context of specific tasks that reflect acquired skills[16]. The training program consisted of three games with up to 30 levels in each game and the participant has to successfully answer 8 out of 10 trials in each level to move forward to the next level. If the participant struggles, the program adapts and moves to an easier level. All three games require the individual to simultaneously process and remember information for a brief period.

The task in the first game was to scan a 4x4 grid with stimuli as quickly as possible and remember the location of the target stimulus. The first level began with letters and became progressively harder so the participant had to remember highly familiar word endings, and then complete words using those word endings. As performance improved, the amount of information on the grid increased and the time to respond decreased. In the second game, the task was to process letter rotations starting with simple rotation (is the letter facing up or down?) to more complex rotations (mirror image). The memory component in this game was to remember the location of a red dot that appeared next to the letter. As performance improved, the complexity of the rotations increased as did the number of dot locations to be remembered. The task of the last game was to solve math problems while remembering the solutions in the correct sequence. At the easiest level, the participant had to solve one problem and remember one solution. As performance improved the complexity of the problems increased (e.g., from single-digit addition and subtraction to multiplication to double-digit addition and subtraction), and remember up to six solutions in the correct sequence.

To determine the efficacy of memory training in improving *Gc*, we randomly allocated participants into one of two groups. Those in the Training group used the memory training three times a week and completed 75 trials on average for all three memory games (25 trials per game) over an 8-week period, lasting 30 minutes per session. Those in the Control group received targeted educational support at school three times a week over an 8-week period for approximately 25 total sessions. These sessions lasted 30 minutes each time and focused on acquired skills relevant for attainment. All participants were pre-tested on measures of *Gc*, academic attainment, and working memory; and then post-tested on the same measures. It is important to note that the Training and Control groups did not differ with respect to crystallized intelligence, working memory, or academic attainment in the pre-training assessment. As the working memory training involved tasks that were distinct from the test measures, we postulated that any observed gains in *Gc* and academic attainment could be explained by the training program, rather than practice effects or test-taking skills.

To examine the gains as a function of memory training, we subtracted the pre-test scores from the post-test scores and compared the difference in scores as a function of group (Training vs. Targeted educational support). In Figure 1, scores below 0, as marked by the line, indicate that the group performed worse at the post-test. Scores above 0 indicate improvements that the group made after 10 weeks. There are marked differences in the gains made between the Training and the Control groups. The superior performance of the Training group compared to the Control group was confirmed in all the cognitive measures: *Gc* (U=8.5, p=.02), academic attainment (U=12.5, p=.04), and working memory (U=8.5, p=.04).

Are these gains meaningful? Yes: participants in the Training group made on average an increase of almost 10 standard points in the measure of *Gc*. There are two lines of evidence to suggest that participants would not have achieved this gain without memory training. First, the control group, who did not participate in the training program, showed no improvement in *Gc* despite receiving targeted educational support that was tailored to improve the knowledge and skills. The second line of evidence that demonstrates participants do not improve in their *Gc* without training comes from a recent study on participants with learning difficulties[17]. They were assessed on measures of fluid and crystallized intelligence, working memory, and academic attainment at two time points. In between the testing periods, all participants received targeted educational support from their schools for two years. However, retest scores indicated that none of the participants showed any significant gains on the measures of acquired skills. One possibility is that if fluid cognitive abilities such as working memory are deficient, the ability to acquire knowledge and related skills is limited. This fits with the idea that working memory functions like a bottleneck for learning in individual learning episodes required to increase knowledge[18]. It is reasonable to suggest that without memory training, those with learning difficulties struggle to ‘catch up’ with their peers[19].

It is worth considering why memory training improved performance. We look first at the superior performance of the Training group in the memory test, which can be explained by the inherent properties of the working memory training program. Participants were required to process some information, continually update representations in their ‘mental workspace’, and then recall the information in the correct sequence[20]. As the surface features of the stimuli in the working memory training were different from that of the memory test and the stimuli in the memory test were randomized, the gains made in the memory test are unlikely due to a practice effect. Rather, these gains can be explained by an increase in either capacity or attentional control via training[21], which facilitated superior recall.

The key finding is that this increase in working memory capacity was not restricted to improvements in fluid skills but transferred to acquired skills as demonstrated by gains in *Gc* and academic attainment. As the Control groups did not demonstrate gains in these tests, it is unlikely that the training-related gains are due to practice effects. These transfer effects that emerged are likely due to the nature of the working memory training. Not only did the training focus on the ability to remember and process information, it integrated this skill with knowledge and skills necessary for academic success.

While longitudinal research is necessary to explore the maintenance effects of the gains, this study represents an exciting first step in understanding more about the underlying relationship between fluid cognitive skills such as working memory and acquired skills like crystallized intelligence. Although they do not share the same neural substrates, working memory does appear to impact our ability to acquire knowledge. This view is consistent with working memory is fundamental to general intelligence, predicting as much as 70% of variance in these skills[22]. Not only are working memory tests powerful predictors of ability, our study demonstrates that training working memory can improve this ability. This finding is significant because it demonstrates that *Gc* is not resistant to change and can be improved without training test-taking skills. There are tremendous implications for this that relate not only to education, but in professional environments and vulnerable populations associated with low levels of crystallized intelligence, such as those with learning disabilities, as well as juvenile delinquents.

Methods

***Participants*:** Fifteen students with learning disabilities participated in this study. None of the participants had any physical, sensory, or behavioral impairments. Eight children participated in the Training condition (boys=86%; *M* age= 12.9 yr, *SD*=1 yr), while the remaining seven children formed the Control group (boys=88%; *M* age= 13 yr, *SD*=0.4). They received targeted learning support through an Individual Education Program (IEP) in schools for the duration of the training period (8 weeks). The Training and Control groups did not differ significantly with respect to age; $t(13)<1$.

Measures: All of the following measures were administered pre- and post-intervention for both the Training and Control groups. Raw scores were converted into standard scores where 100 is the mean and 85 is the standard deviation. Crystallized intelligence was assessed using the Vocabulary subtest from Wechsler Abbreviated Scales of Intelligence[23]. Standardized procedure was followed. The Training and Control groups did not differ significantly with respect to the crystallized intelligence score pre-training; $t(13)=1.3$; $p=22$.

Academic attainment was measured using the Numerical Operations test from the Wechsler Objective Numerical Dimensions[24]. It consists of 10 four-item tests. The first set is designed to assess the ability to write dictated numerals. The subsequent sets refer to computational problems addition, subtraction, multiplication and division. Standardized procedure was followed. The Training and Control groups did not differ significantly with respect to the academic attainment score pre-training; $t(13)<1$.

Working memory was tested using a Letter recall test where the participant was shown a letter on the computer screen, immediately followed by another letter. They had to verify whether the letters were the same and then remember the target letters in the correct sequence. The stimuli were randomized so no stimulus sequence was repeated to avoid potential practice effects. The

Training and Control groups did not differ significantly with respect to the working memory score pre-training; $t(13)=1.8$; $p=10$.

1. Kline, P. in *The new psychometrics: Science, psychology and measurement* (Routledge, London, 1998).

2. Deary, I. J., Strand, S., Smith, P. & Fernandes, C. Intelligence and educational achievement. *Intelligence.* **35,** 13-21 (2007).

3. Cattell, R. B. in *Abilities: Their structure, growth, and action* (Houghton Mifflin, New York, 1971).

4. Jaeggi, S. M., Buschkuehl, M., Jonides, J. & Perrig, W. J. Improving fluid intelligence with training on working memory. *Proc Natl Acad Sci USA.* **105**, 6829–6833 (2008).

5. Healy, A. F., Wohldmann, E. L., Sutton, E. M. & Bourne, L. E. Specificity effects in training and transfer of speeded responses. *J Exp Psychol Learn Mem Cognit*. **32**, 534–546 (2006).

6. Bors, D. A. & Vigneau, F. The effect of practice on Raven's Advanced Progressive Matrices. *Learn Individ Differ*. **13**, 291–312 (2003).

7. Blair, C. How similar are fluid cognition and general intelligence? A developmental neuroscience perspective on fluid cognition as an aspect of human cognitive ability. *Behavioral and Brain Sciences*, **29**, 109-160 (2006).

8. Kyllonen, P. C. & Christal, R. E. Reasoning ability is (little more than) working-memory capacity. *Intelligence*. **14**, 389–433 (1990).

9. Gray, J. R., Chabris, C. F. & Braver, T. S. Neural mechanisms of general fluid intelligence. *Nat Neurosci.* **6**, 316–322 (2003).

10. Kane, MJ, Engle RW (2002) The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. Psychon Bull Rev 9:637–671.

11. Stauffer, J. M., Ree, M. J., & Carretta, T. R. Cognitive components tests are not much more than *g*: An extension of Kyllonen's analyses. *Journal of General Psychology*, **123**, 193–205 (1996).

12. Ackerman, P. L., Beier, M. E. & Boyle, M. O. Working memory and intelligence: The same or different constructs? *Psychol Bull.* **131**, 30–60 (2005).

13. Conway, A. R., Kane, M. J. & Engle, R. W. Working memory capacity and its relation to general intelligence. *Trends Cognit Sci.* **7**, 547–552 (2003).

14. Moody, D. E. Can intelligence be increased by training on a task of working memory? *Proc Natl Acad Sci USA.* **37,** 327-328.

15. Geary, D. C. in *The origin of mind: Evolution of brain, cognition, and general intelligence.* American Psychological Association, Washington, DC: 2005).

16. Alloway, T. P. & Alloway, R. G. JungleMemory Training Program (Memosyne Ltd, UK, 2008).

17. Alloway, T. P. Working memory, but not IQ, predicts subsequent learning in children with learning difficulties. *European Journal of Psychological Assessment.* **25,** 92-98 (2009).

18. Gathercole, S. E., Alloway, T. P., Willis, C. & Adams, A.M. Working memory in children with reading disabilities. *Journal of Experimental Child Psychology*. **93**, 265-281 (2006).

19. Alloway, T. P., Gathercole, S. E, Kirkwood, H. J. & Elliott, J. E. Evaluating the validity of the Automated Working Memory Assessment. *Educational Psychology.* **7**, 725-734 (2008).

20. Baddeley, A. Working memory: Looking back and looking forward. *Nature Reviews Neuroscience.* **4**, 829-839 (2003).

21. Cowan, N., & Alloway, T.P. in *Development of Memory in Childhood, 2nd edition* (eds Cowan N. & Courage, M.) 303-342 (Psychology Press, Hove, 2008).

22. Jarrold, C. & Towse, J. N. Individual differences in working memory. *Neuroscience.* **139,** 39-50.

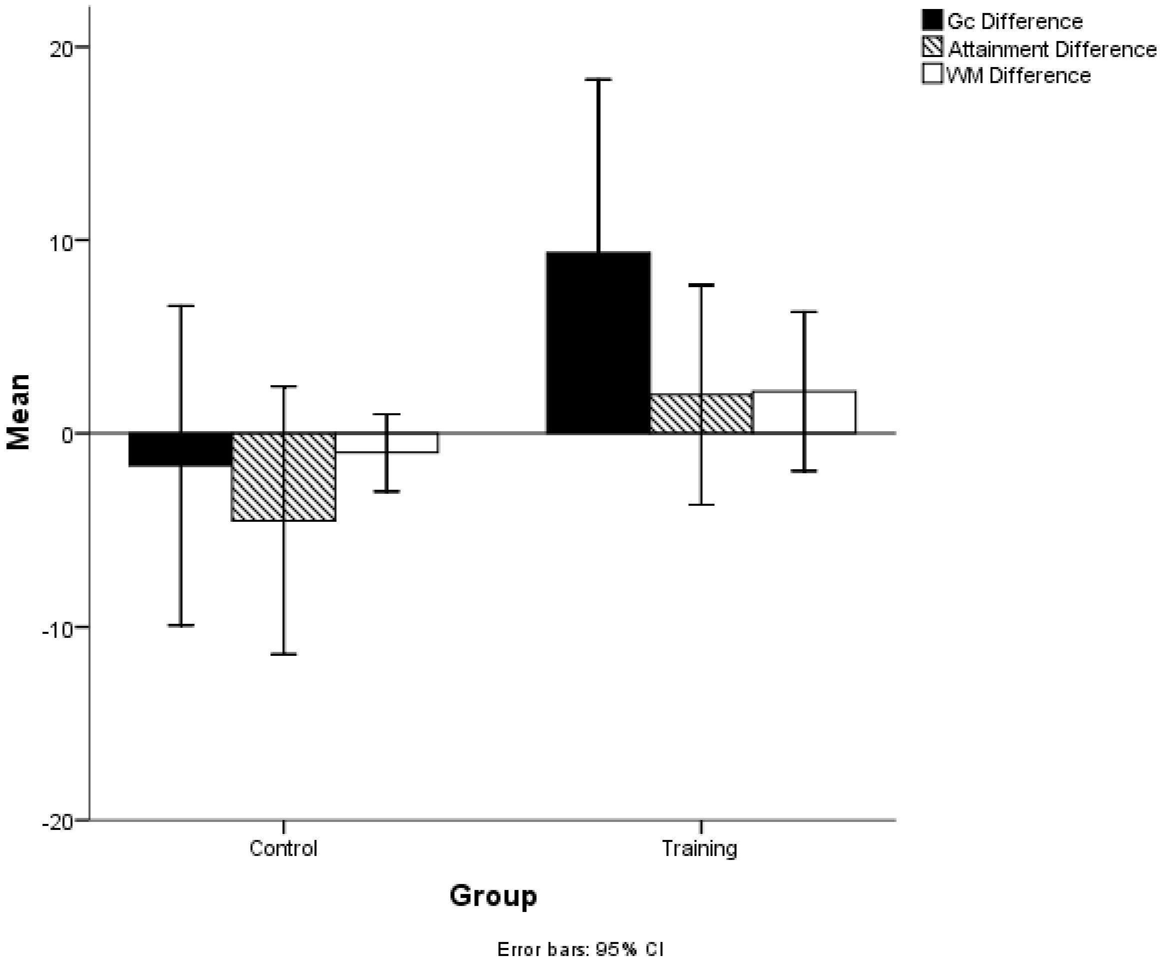
23. Weschler D. *Weschler Abbreviated Scale of Intelligence.* (Psychological Corporation, London, 1999).

24. Wechsler, D. in *Wechsler Objective Numerical Dimensions*. (Pearson Assessment, London, 1996).

Author Contributions. T.P.A. and R.G.A contributed equally to the draft of the article.

Correspondence and requests for materials should be addressed to Tracy Alloway (t.p.alloway@stir.ac.uk). The authors confirm that all experiments were performed in accordance with relevant guidelines and regulations and informed consent was obtained from all participants.

Fig. 1. Shown are the differences in standard scores pre- and post-training for the Control and Training groups.


Gc Difference
Attainment Difference
WM Difference
20
10
0
-10
-20
Mean
Control
Training
Group
Error bars: 95% CI