Cognitive and Working Memory Training

Perspectives From Psychology, Neuroscience, and Human Development

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Review of the Evidence on, and Fundamental Questions About, Efforts to Improve Executive Functions, Including Working Memory

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Abstract

This systematic review looks at all the ways that have been tried for improving executive functions (EFs), including computerized and non-computerized cognitive training, neurofeedback, school programs, physical activity (aerobic and resistance training), mindfulness practices (those more sedentary and more movement-based), and miscellaneous (e.g., drama, piano, and Experience Corps), at all ages. Included are 179 studies from all over the world reported in 193 papers. This is the largest, most comprehensive review thus far of EF interventions.

A little-studied approach – mindful movement practices (such as taekwondo and t'ai chi) – shows by far the best results for improving EFs. Promising school programs come in second. Both approaches show better results than any cognitive training. Third best at improving EFs is non-computerized cognitive training. Might these three approaches show better results than any computerized training because they involve more in-person interaction between trainer and trainee?

The best-performing computerized cognitive training method for improving EFs is Cogmed®. Despite claims that N-back training improves fluid intelligence, only one of the six N-back studies with an active control group (and less than half with only no-treatment controls) found evidence of any fluid-intelligence benefit.

Resistance-training and "plain" aerobic-exercise interventions (like running or walking) show the least benefit for improving EFs of all methods. Results are only slightly better for aerobic exercise with more cognitive or motor-skill challenges. This probably reflects how physical-activity interventions have been structured rather than that aerobic activity does not benefit EFs. We predict that the way an activity is done, such as trainers' ability to make the activity enjoyable and to communicate their unwavering faith in the participants and the program and whether the activity is personally meaningful and relevant, inspiring a deep commitment and emotional investment in participants to the activity and to one another, will likely prove more decisive than what the activity is.

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Review of the Evidence on, and Fundamental Questions About, Efforts to Improve Executive Functions, Including Working Memory

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Introduction

Efforts to improve executive functions (EFs)—which include selective attention, self-control, working memory (WM), cognitive flexibility, and reasoning—to remediate deficits, improve academic performance, improve productivity, increase the likelihood of healthy choices and quality of life, and head off, slow, or reverse cognitive decline during aging. This systematic review is the most extensive review to date of interventions, programs, and approaches that have tried to improve EFs. Previous reviews have focused on one type of intervention, for example, the large literature cognitive training approaches to improving EFs or on physical-activity approaches to improving EFs. These reviews have also often concentrated only on children or only on adults. The review here looks at all the different methods that have been tried for improving EFs and at all ages.

In total, 179 studies (reported across 193 papers) from all over the world (North and South America, Europe, South and East Asia, the Middle East, and Oceania) are included. If a study a) evaluated a method to improve EFs, b) was published in English in a peer-reviewed journal by or before 2015, c) had at least one objective EF outcome measure, d) had least eight people per group, e) included a control group and compared EF improvement and/or posttest performance in the experimental and control groups, f) was not simply correlational, and g) involved more exposure to the approach or program than a single session, it is reviewed here. Since our primary focus is normal development and aging, we excluded all studies of participants with brain damage or dementia. We included studies with persons with attention deficit hyperactivity disorder (ADHD), since ADHD is primarily a problem with EFs, and a small random sampling of studies

of individuals with other clinical conditions, such as depression or autism, or individuals who had a learning disorder. Tabulations were done both excluding results for clinical populations and including them.

The findings reveal some surprises. Perhaps the biggest surprise is that a relatively understudied approach—**mindfulness practices involving movement** (Chinese mind-body practices, taekwondo, t'ai chi, and Quadrato Motor Training)—yielded the strongest results for improving EFs.[1] Mindfulness practices involving movement produced the best results for improving EFs across all four different metrics we used for judging strength of EF benefits. When results were taken as reported, even including potentially spurious ones, mindful movement practices still produced the best results on two of the four metrics (see Table 8.1). Table 8.2 omits studies where positive results might not have survived the needed corrections for multiple comparisons or data analyses reflecting the level at which they randomized. These results are far better than those for any other approach to improving EFs. Often, initial findings look strong but then do not hold up in subsequent studies, so there is a chance that this category looks strongest because of the relatively small number of studies that have investigated it thus far. However, right now, all eight studies of mindful movement practices (100%) have found at least suggestive evidence of EF improvement. No other approach to improving EFs can claim that.

Tables 8.1 and 8.2 report results across our four metrics for 13 of the types of interventions we investigated. This review also looks at neurofeedback, combinations of aerobic exercise with other things, and programs using drama, music, photography, quilting, or Experience Corps®, but there were too few studies of each of those to include them in Tables 8.1 or 8.2.

In Table 8.1, **promising school programs** comprise the only approach to come in first or second on all four metrics. In Table 8.2, promising school programs comes in second every time, behind mindful movement practices. *Both approaches show results superior to those for all cognitive training interventions targeting EFs.* School programs have produced much better results for improving inhibitory control than any other approach. That is important because inhibitory control seems to be the EF most predictive of long-term outcomes.

Public school programs targeting EF skills are able to reach more children, more economically, and more fairly (in that ability to pay is irrelevant) than any other approach to improving EFs. When EF training is embedded in activities throughout the school day, children are challenged on diverse EFs under

[1] Yoga forms its own category in our review because there were a sufficient number of studies of yoga to make that possible. EF benefits from yoga have generally been disappointing, although a few studies found outstanding results. It is unclear why there is such a discrepancy across studies, but it might have to do with how yoga was taught (as a mindfulness practice or just as a physical activity) and/or characteristics of the instructor.

Table 8.1. Summary of Results for All EFs Assessed (Including Reasoning/Fluid Intelligence) Across All Program and Intervention Types

	Percent of Studies Finding Even Suggestive[1] Evidence of EF Benefits (# of Studies)	Percent of Studies Finding Clear[2] Evidence of EF Benefits (# of Studies)	Percent of EF Outcome Measures on which Experimental Group Improved More Than Control Group (# of Measures)	Percent Of EF Measures on which Experimental Group Performed Better at Posttest Than Control Group (# of Measures)
Cogmed Training	60% (15)	23% (13)	42% (138)	28% (104)
N-back Training	46% (13)	31% (13)	24% (93)	20% (91)
Computerized Complex-Span Training	25% (4)[3]	0% (4)	27% (30)	24% (29)
Task-Switching Training	20% (5)	0% (5)	47% (51)	24% (42)
Other Computerized Cognitive Training (including commercial products)[4]	44% (27)	13% (24)	29% (223)	13% (196)
Noncomputerized Cognitive Training	67% (12)	20% (10)	45% (74)	30% (60)
Plain Aerobic Exercise	31% (16)	6% (16)	17% (70)	11% (64)
Aerobic Exercise with Cognitive and/or Motor Skill Demand[5]	53% (19)	7% (14)	36% (81)	15% (47)
	43%(35)	7%(30)	27%(151)	13%(111)
Resistance Training	22% (9)	0% (8)	25% (36)	7% (30)
Yoga	43% (7)	14% (7)	38% (32)[6]	23% (35)
Mindfulness Practices Involving Movement (other than yoga)	100% (8)	29% (7)	70% (23)	50% (16)
	73%(15)	51%(55)	51%(55)	31%(51)

(continued)

Table 8.1. Continued

	Percent of Studies Finding Even Suggestive[1] Evidence of EF Benefits (# of Studies)	Percent of Studies Finding Clear[2] Evidence of EF Benefits (# of Studies)	Percent of EF Outcome Measures on which Experimental Group Improved More Than Control Group (# of Measures)	Percent Of EF Measures on which Experimental Group Performed Better at Posttest Than Control Group (# of Measures)
More Sedentary Mindfulness Practices	61% (23)	17% (23)	36% (91)	30% (96)
Promising School Programs[7]	75% (8)	57% (7)	61% (28)[8]	53% (38)

Note. There were too few studies in any of the following categories to include them here, although they appear in Tables 8.3 and 8.4 and are discussed in the chapter: interventions that combined aerobic exercise with other interventions, neurofeedback, theater, piano, photography, quilting, and Experience Corps.

[1] Suggestive = more EF improvement or better EF posttest performance than control group on ≥ 50% of measures.

[2] Clear = more EF improvement and better EF posttest performance than control group on ≥ 67% of measures. Whenever a study reported ≥ 67% of measures showing positive results for improvement or posttest and did not provide any data on the other, that study is not included in calculations here because it is possible the results of the study might have met our criteria for "clear" had the results not reported been included.

[3] Six complex-span training studies are included in the review. Two were noncomputerized and are included under "noncomputerized training" in Table 8.1 rather than under computerized complex-span training.

[4] Other Computerized Cognitive Training includes both interventions classified as miscellaneous computerized cognitive training and commercial computerized cognitive training products, including the noncommercial BrainGame Brian.

[5] If the FITKids studies are counted as three separate, independent studies, then for enriched aerobic exercise, the results would be 52% (21) for suggestive evidence, 6% (16) for clear evidence, 35% (91) for improvement, and 14% (57) for posttest.

[6] One yoga study did not do pretesting.

[7] Included in the Promising School Programs category are the following school programs: Attention Academy, Chicago School Readiness Program (CSRP), MindUP, Montessori, PATHS, and Tools of the Mind.

[8] Two studies of School Programs did not do pretesting.

Table 8.2. Summary of Results for EFs Assessed (Including Reasoning/Fluid Intelligence) Across All Program and Intervention Types, Omitting Studies Whose Positive Results Might Not Have Held up Had They Corrected for Multiple Comparisons or Conducted Data Analyses Reflecting the Level at Which They Randomized

	Percent of Studies Finding Even Suggestive[1] Evidence of EF Benefits (# of Studies)	Percent of Studies Finding Clear[2] Evidence of EF Benefits (# of Studies)	Percent of EF Outcome Measures on which Experimental Group Improved More Than Control Group (# of Measures)	Percent of EF Measures on which Experimental Group Performed Better at Posttest Than Control Group (# Of Measures)
Cogmed Training	54% (13)	27% (11)	36% (103)	28% (69)
N-back Training	30% (10)	30% (10)	18% (72)	18% (72)
Computerized Complex-Span Training	33% (3)	0% (3)	30% (10)	22% (9)
Task-switching Training	20% (5)	0% (5)	47% (51)	24% (42)
Other Computerized Cognitive Training (including commercial products)[3]	45% (22)	10% (20)	33% (145)	14% (125)
Noncomputerized Cognitive Training	67% (12)	20% (10)	45% (74)	30% (61)
Plain Aerobic Exercise	31% (16) } 41%(34)	6% (16) } 7%(29)	17% (70) } 26%(145)	11% (64) } 13%(105)
Aerobic Exercise with Cognitive and/or Motor Skill Demand	50% (18)	8% (13)	33% (75)	17% (41)
Resistance Training	22% (9)	0% (8)	25% (36)	7% (30)
Yoga	20% (5) } 60%(10)	20% (5) } 33%(9)	16% (19) } 40%(30)	14% (22) } 26%(27)
Mindfulness Practices Involving Movement (other than yoga)	100% (5)	50% (4)	82% (11)	80% (5)

(continued)

Table 8.2. Continued

	Percent of Studies Finding Even Suggestive[1] Evidence of EF Benefits (# of Studies)	Percent of Studies Finding Clear[2] Evidence of EF Benefits (# of Studies)	Percent of EF Outcome Measures on which Experimental Group Improved More Than Control Group (# of Measures)	Percent of EF Measures on which Experimental Group Performed Better at Posttest Than Control Group (# Of Measures)
More Sedentary Mindfulness Practices	59% (22)	18% (22)	38% (86)	28% (85)
Promising School Programs[4]	67% (6)	40% (5)	53% (19)	52% (25)

Note. There were too few studies in any of the following categories to include them here, although they appear in Tables 8.3 and 8.4 and are discussed in the chapter: interventions that combined aerobic exercise and other things, neurofeedback, theater, piano, photography, quilting, and Experience Corps.

[1] Suggestive = more EF improvement or better EF posttest performance than control group on ≥ 50% of measures.

[2] Clear = more EF improvement and better EF posttest performance than control group on ≥ 67% of measures. Whenever a study reported ≥ 67% of measures showing positive results for improvement or posttest and did not provide any data on the other, that study is not included in calculations here because it is possible the results of that study might have met our criteria for "clear" had the results not reported been included.

[3] Other Computerized Cognitive Training includes both interventions we classified as miscellaneous computerized cognitive training and commercial computerized cognitive training products, including the noncommercial BrainGame Brian.

[4] Included in the Promising School Programs category are the following school programs: Attention Academy, Chicago School Readiness Program (CSRP), MindUP, Montessori, PATHS, and Tools of the Mind.

very diverse circumstances. That is important for improvement on multiple EFs and for being able to generalize skills to novel situations. School programs are also able to provide greater doses, frequency, and duration than most other approaches to improving EFs. The data suggest that this combination of a great deal of training and practice under diverse circumstances pays off.

Despite much hype in the popular press and even some influential reviews in high-profile journals, there is a glaring lack of evidence that interventions tried thus far of **resistance training** or **aerobic exercise** consistently improve EFs. Across all the different methods investigated thus far for improving EFs, only resistance training and "plain" aerobic exercise (e.g., running or brisk walking) fall in the bottom half on *all* four measures we used to assess intervention efficacy in both Tables 8.1 and 8.2. (Results are slightly better for aerobic exercise with more cognitive or motor-skill challenges. It shows better results than plain aerobic exercise on three of the four metrics, with comparable results on the fourth. However, it still falls in the bottom half of interventions on three of the four metrics.) *No study of resistance training* and only two studies each of plain aerobic exercise and aerobic exercise with more cognitive or motor-skill challenges found clear evidence of EF benefits. Across all EF outcome measures, participants in resistance training or plain aerobic exercise improved more than control participants on only 17% to 25% of the measures. Compare that to mindfulness movement practices, task switching, or promising school programs, where across all EF outcome measures the experimental group improved more than the control group on 82%, 48%, and 53% of the measures, respectively (see Table 8.2). These results probably reflect how these types of physical-activity interventions have been structured rather than that aerobic activity does not benefit EFs. Persons who are more physically fit and people who spend more time doing physical activity consistently show better EFs. Engaging in physical activity might be driving EF benefits in ways that most intervention studies have not been capturing. (Hypotheses about that are offered in this chapter.)

Another approach that has received less media attention, **noncomputerized cognitive training**, looks potentially promising. Of the 13 approaches listed in Tables 8.1 and 8.2, it ranked third. It fell in the top 50% of programs on all four metrics in both Table 8.1 and Table 8.2. *Noncomputerized cognitive training has produced better EF results than any type of computerized cognitive training.* Across all studies of noncomputerized cognitive training, 67% report at least suggestive evidence of EF benefits, but only a few of those studies used blinded assessment. Note that all three approaches producing the best EF results involve more in-person interaction than computerized cognitive training. Perhaps some of the success of noncomputerized training has to do with the greater degree of instructor–trainee interaction when training is not computerized. On the other

hand, perhaps there is just more room for unintentional biases of the trainers to affect the results when the training is not computerized.

Despite much fuss about possible benefits of **N-back training** for improving fluid intelligence, *only one N-back training study* with an active control group (out of six) found more improvement or better posttest performance on any measure of fluid intelligence in participants compared with control subjects. Compared to no-treatment control groups results look better, but still less than half of N-back studies found evidence of any benefit to fluid intelligence.

The computerized training approach most successful at improving EFs is Cogmed®. It ranked in the top 50% of programs on all four metrics in both Table 8.1 and Table 8.2, the only computerized method to do so. It is the only method to consistently show *sustained* near-transfer benefits. Benefits to WM from Cogmed have been shown to last for 3 to 6 months and even for a year. Benefits from Cogmed are narrow, though, extending only to the aspects of WM trained and perhaps some aspects of attention. Cogmed is marketed as being beneficial to children with ADHD, yet its generalization to ADHD symptomatology has not been confirmed by blinded observers or objective measures.

Results from three different studies suggest that the mentoring component of Cogmed may play a greater role in Cogmed's benefits than people have appreciated. The control version of Cogmed (where difficulty does not increase) also includes interaction with mentors, but it usually produces less benefit than the standard, adaptive version of Cogmed. Is mentoring then irrelevant to the benefits or might the mentors not expect similar benefits from the control condition? Interacting with an adult who believes in the efficacy of the training and expects you to improve is probably critical.

In all age groups, cognitive training, both computerized and noncomputerized, improves the cognitive skills on which one trains. There does not appear to be an age too young or too old. There is very limited evidence of transfer to untrained skills, however.

If someone has a specific deficit in WM (as can be common with aging), Cogmed or N-back training might be quite beneficial. There has been very little study of Cogmed with older adults, but WM deteriorates earlier and more severely during aging than most other cognitive skills. The few studies of Cogmed and N-back training with older adults suggest that such targeted cognitive training might be especially beneficial for that subset of the population.

It is clear that generally, sessions of 30 to 40 minutes (min) yield better EF outcomes than sessions shorter than 30 min, and that is true both for cognitive training and physical activity (although Quadrato Motor Training provides a notable exception). It is not clear, however, that even longer sessions yield better results. For aerobic exercise, the evidence suggests that sessions longer than an

hour yield fewer benefits than sessions of 45 to 60 min (of which about 30–40 min is aerobic).

We predict that many activities not yet studied will likely improve EFs. We also predict that the way an activity is done and the human qualities of the mentors or trainers (such as how enjoyable they make the activity, their supportiveness, and their ability to communicate their unwavering faith in the participants and the program), as well as whether the activity is personally meaningful and relevant, inspiring a deep commitment and emotional investment from participants to the activity and to one another, will likely prove more decisive than what the activity is. We are impressed with the potential benefits of real-world activities, such as sports, theater, and Experience Corps®, that engender deep commitments, bring joy, build self-confidence and pride, challenge EFs, and build community. We would like to see more studies of these and other real-world activities, including more that are done outdoors in nature.

EFs certainly can be improved—at every age from infancy through old age. We are only at the beginning, however, of understanding what characterizes the approaches that are most successful and how success differs by type of approach, EF domain, and/or subject characteristics. We have hardly begun to explore how to make benefits generalize further and last longer. Much has been revealed about what works to improve EFs and what does not, but this is only the tip of the iceberg.

Executive Functions (EFs)

Before discussing the general principles that can be gleaned from the vast literature relevant to improving EFs, it is important to define EFs and to explain why it is important to try to improve them.

EFs (also called executive control or cognitive control) refer to a family of interrelated, top-down processes needed to concentrate and pay attention, when "going on autopilot" or relying on instinct or intuition would be ill-advised, insufficient, or impossible (Diamond, 2006, 2013; Espy, 2004; Hughes, 2005; Jacques & Marcovitch, 2010). There is general agreement that there are three core EFs (inhibitory control, WM, and cognitive flexibility; Diamond, 2013; Miyake et al., 2000; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Logue & Gould, 2013; see Figure 8.1). Using EFs is effortful. It is easier to continue doing what one has been doing than to change or to put thought into what to do next. It is easier to give into temptation than to resist it.

One core EF is inhibition (also called inhibitory control), under which are usually categorized both self-control (behavioral inhibition or response inhibition) and interference control (including selective attention [also called