A meta-regression to examine the relationship between aerobic fitness and cognitive performance

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Abstract:

Many studies have been conducted to test the potentially beneficial effects of physical activity on cognition. The results of meta-analytic reviews of this literature suggest that there is a positive association between participation in physical activity and cognitive performance. The design of past research demonstrates the tacit assumption that changes in aerobic fitness contribute to the changes in cognitive performance. Therefore, the purpose of this meta-analysis was to use meta-regression techniques to statistically test the relationship between aerobic fitness and cognitive performance. Results indicated that there was not a significant linear or curvilinear relationship between fitness effect sizes (ESs) and cognitive ESs for studies using cross-sectional designs or posttest comparisons. However, there was a significant negative relationship between aerobic fitness and cognitive performance for pre–post comparisons. The effects for the cross-sectional and pre–post comparisons were moderated by the age group of the participants; however, the nature of this effect was not consistent for the two databases. Based on the findings of this meta-analytic review, it is concluded that the empirical literature does not support the cardiovascular fitness hypothesis. To confirm the findings of this review, future research should specifically test the dose–response relationship between aerobic fitness and cognitive performance. However, based upon the findings of this review, we also encourage future research to focus on other physiological and psychological variables that may serve to mediate the relationship between physical activity and cognitive performance.

Keywords: Exercise | Physical activity | Cognitive performance

Article:

1. Introduction

Regular participation in physical activity has been proposed to be associated with a variety of mental health benefits. Empirical evidence and meta-analytic reviews have confirmed these mental health benefits for a number of psychological outcome variables (e.g., cognition, sleep, depression). However, while the benefits of physical activity for mental health are relatively well established, the underlying mediators of this relationship have yet to be fully identified. The cardiovascular fitness hypothesis suggests that cardiovascular (aerobic) fitness is a physiological mediator that explains the various mental health benefits of physical activity (North et al., 1990). As applied to cognitive performance, this hypothesis suggests that the gains in cardiovascular fitness achieved through regular participation in physical activity mediate the cognitive performance benefits that result (Barnes et al., 2003, Chodzko-Zajko and Moore, 1994, Dustman et al., 1994, van Boxtel et al., 1996, **van Boxtel et al., 1997). Regular participation in moderately intense physical activity results in an increase in the ability of the heart to deliver oxygen to the working muscles and is indicative of an increase in cardiovascular fitness (American College of Sports Medicine, 2000). These gains in cardiovascular fitness are thought to be associated with changes in underlying physiological mechanisms such as cerebral structure (Colcombe et al., 2003), cerebral blood flow (Endres et al., 2003, Swain et al., 2003), brain-derived neurotrophic factor (Vaynman and Gomez-Pinilla, 2005, Zheng et al., 2005) that have themselves been shown to be associated with cognitive performance (Brown et al., 1996, Moss et al., 2005, Perico et al., 2005, Sohn et al., 2005, Vaynman et al., 2004). Thus, the cardiovascular fitness hypothesis proposes that changes in aerobic fitness are necessary for the cognitive benefits of physical activity to be observed.

In the exercise and cognition literature, the experimental design of the majority of the studies suggests that the researchers were interested in testing the cardiovascular fitness hypothesis as it applies to cognitive performance. That is, many authors have used aerobic fitness as the independent variable designed to distinguish between two (or more) groups that are expected to exhibit differences in cognitive performance. Some of these researchers have used cross-sectional designs to compare the cognitive performance of groups of differing levels of aerobic fitness (e.g., *Chodzko-Zajko et al., 1992, *Dustman et al., 1990, *Hillman et al., 2002). Others have used exercise interventions to manipulate aerobic exercise levels in a treatment group, have used aerobic fitness levels to confirm the efficacy of the intervention, and have then compared cognitive performance either from pretest to posttest or between the treatment group and the control group (e.g., Blumenthal et al., 1991, *Dustman et al., 1984, *Emery et al., 1998, *Madden et al., 1989). The limitation of the extant literature is that few researchers have actually tested aerobic fitness as a mediator of the relationship between physical activity and cognitive performance because they have not tested a dose–response *relationship* between the aerobic fitness differences or gains and the cognitive performance differences or gains.

In a previous meta-analytic review of this literature, Etnier et al. (1997) used indirect evidence to make judgments about the efficacy of the cardiovascular fitness hypothesis. They coded studies for variables that should logically be predictive of larger aerobic fitness gains (e.g., number of weeks of training, evidence of a training effect). Results indicated that none of these variables were predictive of the size of the gain in cognitive performance. This finding was interpreted as indirect evidence against the cardiovascular fitness hypothesis.

More recently, Colcombe and Kramer (2003) examined the cardiovascular hypothesis in a meta-analytic review limited to studies using true experimental designs to test the relationship in older adults. These authors categorized studies as having an unreported change, a 5–11% change, or a

12–25% change in VO_{2max}. Results indicated that there were no significant differences in the size of the cognitive effect size (ES) as a function of these levels of change in fitness.

While the findings of these previous meta-analyses fail to support the cardiovascular fitness hypothesis, the testing of this hypothesis was not a primary purpose of either review, and the hypothesis was only examined indirectly. Thus, the primary purpose of this meta-analytic review is to provide a statistically powerful test of the viability of the cardiovascular fitness hypothesis by examining the dose–response relationship between aerobic fitness and cognition. This was accomplished by including studies using a variety of experimental designs and with participants of all ages and by statistically assessing the relationship between changes (or differences) in cardiovascular fitness and changes (or differences) in cognitive performance through the use of regression analyses. The use of regression analyses in a meta-analytic review represents a relatively novel approach to exploring relationships in exercise psychology and may provide important insights into the relationship of interest (Lau et al., 1998).

In addition to examining the overall relationship between cardiovascular fitness and cognitive performance, the inclusion of moderator variables allowed us to test whether or not the nature of the relationship varied at different levels of logically relevant variables. In particular, because a wider range of effect sizes was anticipated for cross-sectional studies than for chronic studies, a stronger relationship was expected for the cross-sectional studies. Additionally, in recognition of the cognitive reserve hypothesis that suggests that aerobic fitness might be more beneficial for individuals with limits on their cognitive reserves (Chodzko-Zajko and Moore, 1994, Etnier and Landers, 1998), it was hypothesized that the strength of the relationship between aerobic fitness and cognitive performance would be stronger with older adults than with younger participants and with diseased populations than with healthy populations. Thirdly, because maximal measures of aerobic fitness are more accurate than submaximal or composite measures (American College of Sports Medicine, 2000), the strength of the relationship was expected to be stronger for studies using maximal measures of aerobic fitness. Lastly, evidence suggests that particular types of cognitive performance are sensitive to the benefits of aerobic fitness (Colcombe and Kramer, 2003, Etnier et al., 1997, Sibley and Etnier, 2003), and therefore, it was predicted that the relationship between aerobic fitness and cognitive performance would be stronger for particular cognitive test categories.

2. Results

The literature search produced 571 ESs that represent findings from approximately 1306 subjects from 37 studies (identified with a single asterisk in the references) that met the inclusion criteria. See Table 1 for general information about each study.

Table 1. Summary information for each study

Study	*n*	Description	Tot ES	Pub	Assign	Health status	Age range	Avg age	Sex of sample	Fitness measure	Design	Cognitive category
Abourezk, 1990	34	Cross-sectional	2	Un	not R	Heal	60–75	67.5	Female	Sub→Max	X	7
Barry et al., 1966	13	Exer v Control at post	11	Pub	NR	Heal	55–83	70.77	Mixed	Submax	P	1,3,4,6,7
	8	Exer pre v post	11	Pub	NR	Heal	55–78	70.00	Mixed	Submax	G	1,3,4,6,7
Blaney et al., 1990	19	Cross-sectional	4	Pub	not R	Heal	35–50	42.00	Male	Max	X	7

Study	*n*	Description	Tot ES	Pub	Assign	Health status	Age range	Avg age	Sex of sample	Fitness measure	Design	Cognitive category
	14	Exer v Control at post	4	Pub	R	Heal	35–50	42.00	Male	Max	P	7
	7	Exer pre v post	4	Pub	R	Heal	35–50	39.90	Male	Max	G	7
Blomquist and Danner, 1987	54	Exer v Control at post	12	Pub	not R	Heal	18–48	28.10	Mixed	Sub→Max	P	1,3,7
	12	Exer pre v post	12	Pub	not R	Heal	18–48	28.10	Mixed	Sub→Max	G	1,3,7
Blumenthal and Madden, 1988	28	Exer v Control at post	12	Pub	R	Heal	30–58	43.32	Male	Max	P	7,8
	13	Exer pre v post	12	Pub	R	Heal	30–58	42.92	Male	Max	G	7,8
Brisswalter et al., 1997	20	Cross-sectional	2	Pub	not R	Heal	NR	23.50	Male	Max	X	7
Chodzko-Zajko et al., 1992	34	Cross-sectional	2	Pub	not R	Heal	18–88	63.00	Mixed	Sub→Max	X	3
Cosky, 1989	13	Exer pre v post	7	Un	not R	Heal	>65	70.9	Female	Max	G	2,3,4,7
	18	Exer v Control at post	7	Un	not R	Heal	>65	69.7	Female	Max	P	2,3,4,7
Dustman et al., 1984	13	Exer pre v post	6	Pub	R	Heal	55–70	60.60	NR	Max	P	1,3,7,8
Dustman et al., 1990	30	Younger cross-sectional	2	Pub	not R	Heal	20–31	25.20	Male	Max	X	3,7
	30	Older cross-sectional	2	Pub	not R	Heal	50–62	54.85	Male	Max	X	3,7
El-Naggar, 1986	30	Exer pre v post	6	Pub	not R	Heal	25–65	NR	Male	Max	G	1,3,4,6
Elsayed et al., 1980	9	Younger exer pre v post	6	Pub	not R	Heal	24–68	33.67	Mixed	Composite	G	1,2
	9	Younger exer pre v post	6	Pub	not R	Heal	24–68	35.89	Mixed	Composite	G	1,2
	9	Older Exer pre v post	6	Pub	not R	Heal	24–68	52.00	Mixed	Composite	G	1,2
	9	Older Exer pre v post	6	Pub	not R	Heal	24–68	53.89	Mixed	Composite	G	1,2
	18	Younger cross-sectional	6	Pub	not R	Heal	24–68	34.78	Mixed	Composite	X	1,2
	18	Older cross-sectional	6	Pub	not R	Heal	24–68	52.95	Mixed	Composite	X	1,2
Emery, 1994	30	Exer pre v post	5	Pub	not R	COPD	53–68	61.80	Mixed	Max	G	3,4,7
	30	Exer pre v post	5	Pub	not R	COPD	68–82	73.10	Mixed	Max	G	3,4,7
Emery et al., 1998	25	Exer pre v post	5	Pub	R	COPD	>50–NR	65.40	Mixed	Max	G	2,4,6,7
	50	Exer v Control at post	5	Pub	R	COPD	>50–NR	66.40	Mixed	Max	P	2,4,6,7
Emery et al., 2003	11	Exer pre v post	4	Pub	not R	COPD	>50–NR	66.7	Mixed	Max	G	4,5,7
	28	Exer v Control at post	4	Pub	not R	COPD	>50–NR	66.7	Mixed	Max	P	4,5,7
Etnier and Berry, 2001	29	Exer pre v post	4	Pub	not R	COPD	55–80	NR	Mixed	Max, Submax	G	1
	8	Exer pre v post	4	Pub	not R	COPD	55–80	NR	Mixed	Max, Submax	G	1
Fabre et al., 2002	8	Exer pre v post	8	Pub	R	Heal	60–76	65.6	Mixed	Max	G	2,3
	16	Exer v Control at post	8	Pub	R	Heal	60–76	65.4	Mixed	Max	G	2,3
Hansen et al., 2004	20	Exer pre v post	5	Pub	not R	Heal	18–22	19.1	Male	Max	G	3,7
	36	Exer v Control at post	5	Pub	not R	Heal	18–22	19.1	Male	Max	P	3,7
Harma et al., 1988	46	Exer pre v post	2	Pub	not R	Heal	20–49	35.00	Female	Sub→Max	G	3

Study	*n*	Description	Tot ES	Pub	Assign	Health status	Age range	Avg age	Sex of sample	Fitness measure	Design	Cognitive category
Hascelik et al., 1989	20	Exer pre v post	2	Pub	not R	Heal	17–20	18.50	Male	Max	G	7
Hassmen et al., 1992	8	Exer pre v post	4	Pub	NR	Heal	55–65	63.10	Female	Max	G	3,7
	7	Exer pre v post	4	Pub	NR	Heal	66–75	69.30	Female	Max	G	3,7
	15	Exer v Control at post	4	Pub	NR	Heal	55–65	62.90	Female	Max	P	3,7
	15	Exer v Control at post	4	Pub	NR	Heal	66–75	69.20	Female	Max	P	3,7
Hill et al., 1993	121	Exer v Control at post	3	Pub	NR	Heal	60–73	64.00	Mixed	Max	P	3,6,7
	87	Exer pre v post	3	Pub	NR	Heal	60–73	64.00	Mixed	Max	G	3,6,7
Hillman et al., 2002	24	Older cross-sectional	2	Pub	not R	Heal	60–70	64.25	Mixed	Max	X	4
	24	Younger cross-sectional	2	Pub	not R	Heal	18–28	22.70	Mixed	Max	X	4
Ismail and El-Naggar, 1981	48	Exer v Control at post	10	Pub	R	Heal	24–68	42.00	Male	Max	P	1,3,4,6
	35	Exer pre v post	10	Pub	R	Heal	24–68	42.00	Male	Max	G	1,3,4,6
Khatri et al., 2001	42	Exer pre v post	12	Pub	R	Dep	50–72	56.73	Mixed	Max	G	2,3,4,7
	84	Exer v Control at post	12	Pub	R	Dep	50–72	56.73	Mixed	Max	P	2,3,4,7
Kozora et al., 2002	24	Exer pre v post	11	Pub	not R	COPD	NR	66.5	Mixed	Submax	G	2,3,4,5,6,7
	53	Exer v Control at post	11	Pub	not R	COPD	NR	66.7	Mixed	Submax	P	2,3,4,5,6,7
Kramer et al., 2002	58	Exer pre v post	36	Pub	R	Heal	60–75	66.61	Mixed	Max	G	3,4,7
	124	Exer v Control at post	36	Pub	R	Heal	60–75	66.61	Mixed	Max	P	3,4,7
Madden et al., 1989	25	Exer pre v post	61	Pub	R	Heal	60–83	66.00	Mixed	Submax	G	7
	51	Exer v Control at post	29	Pub	R	Heal	60–83	66.00	Mixed	Submax	P	7
McCrory, 1980	24	Exer v Control at post	2	Un	not R	Heal	22–62	34.60	Male	Sub→Max	P	7
	11	Exer pre v post	2	Un	not R	Heal	22–62	34.60	Male	Sub→Max	G	7
Mero et al., 1989	18	Cross-sectional	1	Pub	not R	Heal	NR	11.20	Male	Submax	X	7
Moul et al., 1995	20	Exer v Control at post	12	Pub	R	Heal	65–72	69.1	Mixed	Max	P	1,3,5
	20	Exer pre v post	12	Pub	R	Heal	65–72	69.1	Mixed	Max	G	1,3,5
Palmer, 1995	15	Exer pre v post	4	Un	R	Heal	60–72	67.6	Mixed	Sub→Max	G	2,4,5
	15	Exer pre v post	4	Un	R	Heal	60–72	66.4	Mixed	Sub→Max	G	2,4,5
	29	Exer v Control at post	4	Un	R	Heal	60–72	66.4	Mixed	Sub→Max	P	2,4,5
Russell, 1982	13	Exer pre v post	2	Un	R	Heal	55–70	61.20	Mixed	Max	G	7
	28	Exer v Control at post	2	Un	R	Heal	55–70	61.80	Mixed	Max	P	7
Shay and Roth, 1992	32	Younger cross-sectional	15	Pub	not R	Heal	18–28	22.70	Mixed	Sub→Max	X	2,3,4,5,7
	35	Middle cross-sectional	15	Pub	not R	Heal	35–45	43.90	Mixed	Sub→Max	X	2,3,4,5,7
	38	Older cross-sectional	15	Pub	not R	Heal	60–73	65.00	Mixed	Sub→Max	X	2,3,4,5,7
Suominen-Troyer et al., 1986	30	Exer v Control at post	3	Pub	NR	Heal	27–66	43.60	Female	Composite	P	1,8
	10	Exer pre v post	3	Pub	NR	Heal	27–66	43.60	Female	Composite	G	1,8
Whitehurst, 1991	14	Exer v Control at post	2	Pub	R	Heal	61–73	65.80	Female	Sub→Max	P	7

Study	*n*	Description	Tot ES	Pub	Assign	Health status	Age range	Avg age	Sex of sample	Fitness measure	Design	Cognitive category
	7	Exer pre v post	2	Pub	R	Heal	61–73	65.80	Female	Sub→Max	G	7
Zervas et al., 1991	18	Exer v Control at post	1	Pub	R	Heal	11–14	13.10	Male	Max	P	4
	9	Exer pre v post	1	Pub	R	Heal	11–14	13.10	Male	Max	G	4

Note. Tot ES = Total effect sizes; Pub = Publication status; Assign = Method of subject assignment; Avg = Average; Exer = Exercise Group; post = posttest; pre = pretest; v = versus; Pub = published; Un = unpublished; NR = not reported; R = random; Heal = Healthy participants; Dep = Depressed participants; COPD = Chronic Obstructive Pulmonary Disease participants; Submax = Submaximal VO2 test; Sub→Max = Submaximal VO2 test used to predict maximal VO2; Max = Maximal VO2 test; X = cross-sectional; P = chronic intervention post-test comparison; G = chronic intervention pre–post comparison (gain); 1 = fluid intelligence; 2 = crystallized intelligence; 3 = general memory and learning; 4 = visual perception; 5 = retrieval ability; 6 = speediness; 7 = processing speed; 8 = errors.

Using a single average corrected ES for each of the 37 studies, descriptive statistics were computed. The mean ES for cognition was 0.34 (SD = 0.30), which was significantly greater than zero, $t(36) = 7.06$, $P < 0.001$. The tolerance of this ES to null experimental results indicated that 89 studies with null findings would have to be found to render the cognitive ES meaningless. The mean ES for fitness was 1.13 (SD = 1.51), which was also significantly greater than zero, $t(36) = 4.54$, $P < 0.001$. The tolerance of this ES to null experimental results was calculated as 381 studies.

Once steps were taken to address the non-independence of the data, the number of ES was reduced to 211.

2.1. Cross-sectional designs

There were a total of 27 ES from 8 studies representing data from 214 subjects. The mean ES for cognition was 0.40 (range = −1.08 to 2.56, SD = 0.67), and the mean ES for fitness was 3.28 (range = −0.54 to 8.02, SD = 1.66).

The test for linear regression was not significant, $\chi^2(1) = 0.53$, $P > 0.05$, but the test of model fit was significant, $\chi^2(25) = 46.04$, $P < 0.01$, suggesting that a significant portion of the variance remained unexplained, $I^2 = 46\%$. Results indicated that neither the quadratic, $\chi^2(2) = 3.63$, $P > 0.05$, nor the cubic relationship, $\chi^2(2) = 6.21$, $P > 0.05$, contributed significantly to the explanation of the variance. Therefore, outliers were explored based upon the studentized deleted residuals from the linear regression (Hedges et al., 1985), and two ESs were identified. These ESs were omitted, and the linear regression was recalculated. Results indicated that the test for regression remained not significant, $\chi^2(1) = 1.27$, $P > 0.05$, and that the model fit was now appropriate, $\chi^2(23) = 22.95$, $P > 0.05$, $I^2 = 0\%$.

2.1.1. Moderator variables

The interaction of age group by aerobic fitness did predict a significant portion of the variance in cognitive performance, $\chi^2(5) = 13.61$, $P < 0.02$, and the model fit was appropriate, $\chi^2(19) = 10.61$, $P > 0.05$. Separate regressions were conducted for each age group to clarify the nature of this effect. Results indicated that aerobic fitness was a significant negative predictor of cognitive performance for the children and young adults, $\chi^2(1) = 4.89$, $P < 0.03$, was a significant positive predictor for the adults, $\chi^2(1) = 7.57$, $P < 0.01$, and was not a significant predictor for the older adults, $\chi^2(1) = 0.36$, $P > 0.05$.

All of the samples in this subset were taken from healthy populations, so this moderator was not examined.

All of the studies in this subset used either a maximal measure of fitness or predicted maximal fitness from a submaximal test, so fitness measurement was not examined as a moderator.

The cognitive test category did not interact with aerobic fitness to predict cognitive performance, $\chi^2(3) = 5.96$, $P > 0.05$, and the model fit was appropriate, $\chi^2(21) = 18.27$, $P > 0.05$.

2.2. Posttest comparisons

There were a total of 78 ES from 24 studies representing data from 934 subjects. The mean ES for cognition was 0.27 (range = −0.93 to 2.14, SD = 0.50), and the mean ES for fitness was 0.57 (range = −1.12 to 2.48, SD = 0.86).

The test for regression was not significant, $\chi^2(1) = 2.06$, $P > 0.05$, nor was the test of model fit, $\chi^2(76) = 64.73$, $P > 05$, $I^2 = 0\%$, suggesting that fitness was not a linear predictor of cognitive performance and that the model fit was acceptable.

2.2.1. Moderator variables

None of the moderators interacted significantly with fitness, and, in all cases, the test of model fit was not significant, $P > 0.05$, suggesting that a linear model was appropriate for explaining the findings and that outliers were not impacting the results.

2.3. Pre–post comparisons

There were a total of 106 ES from 30 studies representing data from 649 subjects. The mean ES for cognition was 0.25 (range = −0.98 to 1.24, SD = 0.35), and the mean ES for fitness was 0.55 (range = −0.35 to2.55, SD = 0.48).

The test for linear regression was significant, $\chi^2(1) = 5.02$, $P < 0.02$, and the test of model fit was not significant, $\chi^2(104) = 95.49$, $P > 05$, $I^2 = 0\%$, indicating that the change in fitness from pretest to posttest was a significant linear predictor of the change in cognitive performance from pretest to posttest, and that the model fit was acceptable. Examination of the beta weight indicated that aerobic fitness was negatively predictive of cognitive performance. That is, larger gains in aerobic fitness from pretest to posttest were predictive of lesser improvements in cognitive performance.

2.3.1. Moderator variables

Age interacted with aerobic fitness to predict a significant portion of the variance in cognitive performance, $\chi^2(5) = 14.37$, $P < 0.02$, and the test of model fit indicated that this model was appropriate, $\chi^2(100) = 86.13$, $P > 0.05$. Regressions conducted for each age group indicated that aerobic fitness was not a significant predictor of cognitive performance for the children and young adults, $\chi^2(1) = 3.73$, $P > 0.05$, or for the adults, $\chi^2(1) = 1.15$, $P > 0.05$, but was a significant negative predictor of cognitive performance for the older adults, $\chi^2(1) = 4.89$, $P < 0.03$.

Health status, the method of measuring fitness, and the cognitive test category did not interact with aerobic fitness to contribute significantly to the prediction of cognitive performance, $P > 0.05$, and in all cases the model fit was acceptable.

2.4. Correlational studies

In the 10 studies in which the strength of the relationship between fitness and cognition were reported, 37 statistics were reported for subjects ranging in age from 17 to 85 years. Of these, 32 relationships were in the direction such that a higher fitness score was associated with improved cognitive performance. Twenty-nine Pearson correlations were reported, for which the overall mean r was 0.29, with a range from 0.04 to 0.68. In these studies, tests of memory and choice RT were the most frequently used measures of cognition.

3. Discussion

The purpose of this meta-analytic review was to test the viability of the cardiovascular fitness hypothesis as an explanation for the relationship between physical activity and cognitive performance. Initial analyses were conducted to examine the size of the cognitive and fitness ESs in the studies included in this review. The cardiovascular fitness hypothesis was then tested in several ways. First, a regression analysis was conducted to determine the degree to which fitness predicted cognitive performance. Second, regression analyses were conducted to determine whether or not the relationship between fitness and cognitive performance was influenced by predicted moderators. Third, studies in which the relationship between fitness and cognition was directly tested were examined to identify the nature of those findings.

Across 37 studies, the average ES for cognitive performance was 0.34 standard deviation units. This is not significantly different, $t(36) = 0.09$, $P > 0.05$, from the ES found in the Etnier et al. (1997) meta-analytic review of 134 studies (ES = 0.25), and supports a conclusion that physical activity is associated with a small cognitive ES (Cohen, 1992). Given the relatively few studies from the Etnier et al. meta-analysis (13%) that were included in this review, the similarity of these effects is important because it suggests that the studies in this review are representative of the research in the area, and that the positive relationship between physical activity and cognitive performance is relatively reliable. Thus, across 37 studies designed to test the effects of fitness on cognition, the summary statistic indicates that there is a positive association between physical activity and cognitive performance and confirms the findings of previous meta-analytic reviews of this literature (Colcombe and Kramer, 2003, Etnier et al., 1997, Sibley and Etnier, 2003).

Results indicated that for cross-sectional studies and for chronic posttest comparisons, there was not a significant relationship between aerobic fitness and cognitive performance. In other words, the advantage that the trained individuals had over the untrained individuals in cognition (cross-sectional ES = 0.40, posttest ES = 0.27) was not predicted by the difference in fitness levels between the groups. However, for the pre–post comparisons, the change in cognitive performance from pretest to posttest (ES = 0.25) was predicted by the amount of change in aerobic fitness from pretest to posttest, albeit in a negative direction. These findings clearly do not provide support for the cardiovascular fitness hypothesis. In fact, the finding for the pre–post comparisons is perplexing and suggests that those studies in which smaller gains in fitness were attained demonstrated the larger cognitive ES.

Based upon past findings in this area of research, it was hypothesized that the relationship between fitness and cognition might differ depending upon the age of the participants, the health status of the sample, the particular method used to measure fitness, or the cognitive test category.

The only moderator that significantly impacted the relationship was age group. Results demonstrated that age group significantly moderated the relationship between aerobic fitness and cognitive performance for the cross-sectional studies and for the pre–post comparisons. However, the pattern of results was not consistent across these two study designs. For the cross-sectional studies, aerobic fitness was negatively predictive of cognitive performance for children and young adults, positively predictive for adults, and not significantly related for older adults. For the pre–post comparisons, aerobic fitness was negatively predictive of cognitive performance for older adults but was not a significant predictor for the other two age groups. Making sense of these findings is challenging. Previous meta-analytic reviews with children (Sibley and Etnier, 2003) and older adults (Colcombe and Kramer, 2003) have both demonstrated that physical activity participation is associated with better cognitive performance. However, the results of this review indicate that for children and young adults and for older adults, smaller differences or gains in fitness were predictive of larger differences or gains in cognitive performance.

A final way to examine the cardiovascular fitness hypothesis was to examine the ten studies in which the correlation between fitness and cognition was directly examined for the subjects in that particular study. In these studies, the overwhelming majority (32 of 37) of the findings support a positive relationship between fitness and cognition. This finding may seem startling in light of the previously described findings of this review. However, it must be recognized that the summary results of correlational studies provide different information than is provided by the meta-analytic portion of this study. That is, the findings from the correlational studies represent relationships between fitness and cognition at the level of the individual. Those individuals who were more fit also performed better cognitively. The interpretation of these findings is similar to the interpretation of the cross-sectional studies but are not comparable to findings from chronic interventions in which aerobic fitness was manipulated. That is, in the correlational and cross-sectional studies, differences in education, nutrition, and an infinite number of other potential confounds may be driving the results. In addition, in the correlational studies reviewed here, most used composite measures of fitness that included variables like body mass, body fat, vital capacity, blood pressure, and submaximal VO_2 rather than using an actual maximal measure of VO_2. Thus, the relationship that was found in these studies should most appropriately be interpreted as supporting a relationship between a more broadly defined measure of health or fitness and cognition. Lastly, for the correlational studies in which a Pearson *r* was used, the average correlation across studies indicated that fitness explained only 8% of the variance in cognition. Thus, while a reliable positive relationship was demonstrated in these correlational studies, aerobic fitness does not appear to explain a meaningful percentage of the variance in cognition.

Overall, the results of this meta-analytic review do not support the cardiovascular fitness hypothesis. The failure of the data from cross-sectional designs and from posttest comparisons to demonstrate a relationship, the negative relationship between aerobic fitness and cognitive performance demonstrated by the pre–post comparisons, and the fact that in the correlational studies only a small percent of variance is explained by the positive relationship between aerobic fitness and cognitive performance suggests that variables other than aerobic fitness may play a more important role in predicting cognitive performance. However, there are two important caveats to this conclusion.

First, the results of a meta-analytic review are, by definition, constrained by the fact that summary statistics from individual studies are combined, and that meta-analytic reviews cannot be used to make judgments about cause-and-effect relationships (Lau et al., 1998). This is a limitation because the results of a single study that is specifically designed to test a dose–response relationship between aerobic fitness and cognitive performance would be a more powerful form of evidence by which to test this particular hypothesis. However, an empirical study of this nature has not been published with cognitive outcome variables. Dose–response questions are beginning to be addressed in the area of physical activity and depression (Dunn et al., 2002), and studies of this type are needed in the area of cognitive performance to further our knowledge regarding potential mediators of the relationship between physical activity and cognition. Further, the ESs used to examine the relationship between aerobic fitness and cognitive performance are dominated by examinations of older adults (63%) with only a small percentage of ESs coming from studies with young adults (10%) and a very small percentage of ESs coming from studies with children (1%). Thus, conclusions from this review may not generalize to younger populations.

Second, it is possible that aerobic fitness does, in fact, mediate the relationship between physical activity and cognitive performance, but that it is such a "gross" measure of the physiological changes that occur in response to chronic physical activity that it is not a very sensitive measure. This would explain why the results of individual studies that manipulate physical activity and demonstrate a change in aerobic fitness do not consistently demonstrate a beneficial effect on cognitive performance. It may be that a more clear and consistent relationship could be evidenced by studies that assess mechanisms that are more closely tied to cognitive performance. That is, aerobic fitness may be the first event in a cascading series of events that ultimately impact cognitive performance. If this is the case, then changes in aerobic fitness might, in fact, be necessary for changes in cognitive performance to occur, but aerobic fitness itself might not be a sensitive indicant of the cognitive benefits that can be obtained through physical activity participation. There are several hypotheses that take this possibility into consideration. For example, the cerebral circulation hypothesis suggests that the changes in cardiovascular fitness that occur with chronic exercise result in an enhancement of oxygen transportation to the brain (Chodzko-Zajko and Moore, 1994) which then results in better cognitive performance because of the increased resources available in the cerebral environment. The neuroadrenergic hypothesis suggests that changes in cardiovascular fitness result in changes in neurotransmitter availability to the cerebral environment. These specific neurotransmitters (noradrenaline, adrenaline, and serotonin) are thought to be associated with memory storage and retrieval (Zornetzer, 1985) and thus would provide benefits to cognitive performance. Alternatively, physiological or psychological mechanisms that are impacted by physical activity participation, but that are not reliant on changes in aerobic fitness, may be responsible for the benefits to cognitive performance.

Although the critical empirical study has not been conducted to directly test the efficacy of the cardiovascular fitness hypothesis for explaining the benefits of physical activity on cognition, based upon the results of this review, we would encourage future researchers in this area to focus on variables other than aerobic fitness as potential mediators of the relationship. Although future intervention studies specifically designed to test the dose–response relationship between physical activity and cognition are needed and may reveal the role of aerobic fitness in the relationship, the findings of this review and of past meta-analytic reviews (Colcombe and Kramer, 2003, Etnier et al., 1997) suggest that our focus on aerobic fitness may have been misguided. Therefore, we would encourage future research to consider other possible explanations (both physiological and psychological) for the positive relationship between physical activity and cognition.

4. Experimental procedures

4.1. Selection and inclusion of studies

All relevant English-language studies from 1927 to October 2005 were located through computer searches of on-line databases using appropriate keywords. The on-line databases that were searched were: Pubmed, Psych Info, Dissertation Abstracts International, Educational Research in Completion, and Sports Discus. All possible combinations of "cognition", "cognitive performance", "academic", and "mental performance" with "fitness", "aerobic", and "VO2" were entered into the search engines. Articles were also identified from reference lists of obtained articles. Unpublished master's theses and doctoral dissertations were included when possible and when the data from these unpublished papers were not subsequently presented in a published format.

Studies were included in this analysis if they examined the relationship between current fitness level or participation in an exercise program and a measure of cognitive performance; used a chronic exercise paradigm, a cross-sectional design in which cognitive performance was examined in a "fit" and a "less fit" group, or a correlational design in which cognition and fitness were correlated; assessed aerobic fitness using a submaximal or maximal measure of VO_{2max}, or a composite measure of fitness that included a measure of VO_{2max}; and included sufficient information for the calculation of ESs for cognitive performance and for aerobic fitness. Sufficient information for the calculation of effect sizes was defined as either (1) means, standard deviations or standard errors, and sample sizes; or (2) *t* statistic or *F* statistic, *df*, and sample sizes.

4.2. Coding of studies

Studies were coded for variables that reflect the types of studies being reviewed (to be reported in a descriptive sense) and for variables that have been identified in the literature as possible moderators of the relationship between aerobic fitness and cognition.

4.2.1. Study design

Studies were coded as cross-sectional or chronic intervention. ESs from chronic interventions were further coded as representing a pre–post comparison for a treatment group or a posttest comparison between a treatment group and a control group. It was expected that the relationship between aerobic fitness and cognition would be stronger in studies using cross-sectional designs than in studies using chronic interventions.

4.2.2. Participant variables

Differences in the relationship between age and fitness were hypothesized to exist as a function of the age group being tested; thus, average age and age ranges were recorded. Average age was used to categorize samples as children and young adults (5–29 years), adult (30–59 years), and older adult (over 60). When average age was not provided, the age range was used to identify the age group of the sample. In particular, it was hypothesized that the cognitive performance of older adults may benefit more from aerobic fitness than does the cognitive performance of the other age groups (Chodzko-Zajko and Moore, 1994, Etnier and Landers, 1998). It was also hypothesized that the relationship between aerobic fitness and cognition would be stronger for samples drawn from diseased populations (i.e., clinical depression, chronic obstructive pulmonary disease) than for samples drawn from healthy populations, so health status was coded as either healthy or not healthy. Differences in the relationship between aerobic fitness and cognition were not expected to exist as a function of the gender make-up of the sample (all male, all female, mixed), but this was recorded for descriptive purposes.

4.2.3. Measurement of fitness

Despite the fact that peak VO_{2max} is considered the “gold standard” measure of aerobic fitness (American College of Sports Medicine, 2000), the method used to assess aerobic fitness varied substantially across the studies. Therefore, type of fitness measurement was coded as a maximal measure of VO_2, a submaximal measure of VO_2 used to predict maximal VO_2, a submaximal measure of VO_2, or a composite measure including a submaximal measure of VO_2. It was expected that the relationship between the ES for the fitness variable and that for the cognitive performance variable would be stronger for those studies using maximal or predicted maximal measures of fitness than for studies using submaximal or composite measures.

4.2.4. Measurement of cognition

Cognitive tests were coded into categories based upon Carroll et al. (1993)'s structure of cognitive abilities as derived from factor analytic analyses. When tests were not specifically identified by Carroll as being in a particular category, the cognitive demands of the tests were determined based upon the authors' descriptions of the test and/or the extensive test descriptions provided by Lezak et al. (2004). The categories used were fluid intelligence, crystallized intelligence, general memory and learning, visual perception, auditory perception, retrieval ability, speediness, and processing speed (test names and category coding are available from the first author upon request). An additional category was created to include error measures on all tests. Because different cognitive tests make different demands on the performer and are controlled by different areas of the brain, it was hypothesized that differences would exist in the relationship between fitness and cognition as a function of the cognitive dimension being assessed. Further, it has been shown that certain areas of the brain are most susceptible to the effects of aging and, consequently, might be most responsive to the effects of physical activity (e.g., Kramer et al., 1999). It was hypothesized that a stronger relationship between fitness and cognitive performance would be observed for fluid intelligence, general memory and learning, speediness, and processing speed.

4.3. Analyses

Cognitive and aerobic fitness ESs were calculated using means and standard deviations or transformations of F or t values. In the case of a smaller mean indicating improved performance (e.g., reaction time, errors committed, time to perform a ½-mile walk), the ES was multiplied by −1 so that a positive ES always indicated an improvement in cognitive performance or in aerobic fitness. The standard deviation used in the denominator of the ES was the pretest standard deviation for within-subjects designs and was the pooled standard deviation (i.e., Hedges g) for between-subjects designs. To correct for positive bias due to small sample size, the ES was multiplied by a correction factor (c) where $c = 1 - [3/(4m - 9)]$ and where $m = n_{\text{experimental}} + n_{\text{control}} - 2$ for between-subjects designs and where $m = n - 1$ for within-subjects designs (Hedges et al., 1985).

An average cognitive and aerobic fitness ES (corrected for sample size) was then calculated for each study, and single sample t tests were used to determine if these means were significantly different from zero. Using the formula presented by Hunter et al. (1990), the "file-drawer effect" was also examined. This was done by determining the number of studies with null average ESs that would be necessary to bring the overall mean effect down to a level that would be considered meaningless (ES = 0.10).

Because many studies provided data that could be used to calculate more than one ES (range = 1–90 ESs), steps were taken to minimize the threats to the assumption of independence. First, separate analyses were conducted for the three different study designs. That is, separate analyses were conducted for (1) differences between a "fit" group and a "less fit" group (cross-sectional comparisons); (2) differences between a treatment group and a control group at the posttest (posttest comparisons); and (3) changes from the pretest to the posttest for a treatment group (pre–post comparisons). Second, when more than one control group was used in a study, ES were used for comparisons with the control group that received no treatment (i.e., a wait-list control or a control group that was untreated). This decision was based on an expectation that the largest ES would be observed for these comparisons, and, thus, the cardiovascular fitness hypothesis would be given the best chance for support. Third, when ES for a particular sample within a study were derived from the same cognitive test (i.e., Blomquist and Danner, 1987 presented data for the Sternberg task separately for each of 2–6 digits) or from different cognitive tests from the same cognitive category, these ESs were averaged to generate one ES.

After reducing the data, descriptive statistics for the cognitive and fitness ESs for each study design are presented. Then fixed effects models were conducted to determine the ability of the fitness ES to predict the cognitive ES using least squares regression weighted by the inverse of the variance for the cognitive ES (Hedges et al., 1985). To allow for judgments regarding the risk of a Type I error, a measure of heterogeneity is provided using $I^2 = 100\% \times (\mathrm{He} - df)/\mathrm{He}$ where He is the weighted sum of squares of deviations (Cochran, 1954, Higgins and Thompson, 2004, Higgins et al., 2003). I^2 provides an expression of the percentage of variability that is due to the heterogeneity between studies rather than sampling error (Higgins and Thompson, 2002). The sum of squares regression (Hr) is examined as a Chi-squared test of the regression with $df = p$ (where p = number of predictors). A test for model specification was performed by examining He relative to a Chi-squared distribution with $df = N - p - 1$ (where N = number of ESs) (Hedges et al., 1985). When the He was significant, curvilinear regressions were conducted and the studentized residuals for the data were examined for potential outliers relative to a criterion of 2.0 (Hedges et al., 1985). If outliers were identified, they were removed, and the regression analysis was repeated.

Lastly, hierarchical regression analyses were conducted to examine the influence of interactions between hypothesized moderator variables and fitness on the cognitive ES. Prior to the regression analyses, categorical variables were dummy coded to test the specific hypotheses. For all moderator analyses, the main effects for fitness and the moderator variable were entered first, and then the interaction term was entered. Hr was examined to test the significance of the interactions. Because regression analyses are robust against alpha inflation due to multiple tests, alpha was 0.05 for all tests (Thomas and French, 1986).

All statistical analyses were conducted using SPSS for Windows version 12.0.

In addition to the studies included in the regression analyses, 10 studies (**Aleman et al., 2000, **Bunce and Birdi, 1998, **Bunce, 2001, **Bunce et al., 1993, **Era et al., 1986, **Etnier et al., 1999, **Izquierdo-Porrera and Waldstein, 2002, **Lord and Menz, 2002, **Offenbach et al., 1990, **van Boxtel et al., 1997) were found that specifically correlated fitness data with cognitive data (identified with a double asterisk in the references). Studies in which correlations between fitness and cognition were reported could not be included in the overall statistical analysis because they did not provide separate ESs for cognitive performance and for aerobic fitness (to be used in the regression analysis). However, in an effort to be as inclusive as possible, a brief summary of the overall results from these studies is provided.

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References

*Abourezk, T., 1990. The relationship among cognitive complexity, oxygen, and activity level in older women. Doctoral Dissertation, Physical Education, Florida State University, Jacksonville, FL.

**Aleman, A., de Haan, E.H., Verhaar, H.H.J., Samson, M.M., de Vries, W.R., Koppeschaar, H.P.F., 2000. Relationship between physical and cognitive function in healthy older men: a role for aerobic power? J. Am. Geriatr. Soc. 48 (1), 104–105.

American College of Sports Medicine, 2000. ACSM's Guidelines for Exercise Testing and Prescription, 6th edition. Lippincott Williams and Wilkins, Philadelphia.

Barnes, D.E., Yaffe, K., Satariano, W.A., Tager, I.B., 2003. A longitudinal study of cardiorespiratory fitness and cognitive function in healthy older adults. J. Am. Geriatr. Soc. 51, 459–465.

*Barry, A.J., Steinmetz, J.R., Page, H.F., Rodahl, K., 1966. The effects of physical conditioning on older individuals: II. Motor performance and cognitive function. J. Gerontol. 21 (2), 192–199.

*Blaney, J., Sothmann, M., Raff, H., Hart, B., Horn, T., 1990. Impact of exercise training on plasma adrenocorticotropin response to a well-learned vigilance task. Psychoneuroendocrinology 15 (5–6), 453–462.

*Blomquist, K.B., Danner, F., 1987. Effects of physical conditioning on information-processing efficiency. Percept. Mot. Skills 65, 175–186.

*Blumenthal, J.A., Madden, D.J., 1988. Effects of aerobic exercise training, age, and physical-fitness on memory-search performance. Psychol. Aging 3, 280–285.

Blumenthal, J.A., Emery, C.F., Madden, D.J., Schniebolk, S., Walsh-Riddle, M., George, L.K., McKee, D.C., Higginbotham, M.B., Cobb, F.R., Coleman, R.E., 1991. Long-term effects of exercise on psychological functioning in older men and women. J. Gerontol. 46 (6), P352–P361.

*Brisswalter, J., Arcelin, R., Audiffren, M., Delignieres, D., 1997. Influence of physical exercise on simple reaction time: effect of physical fitness. Percept. Mot. Skills 85 (3 Part 1), 1019–1027.

Brown, D.R.P., Hunter, R., Wyper, D.J., Patterson, J., Kelly, R.C., Montaldi, D., McCullouch, J., 1996. Longitudinal changes in cognitive function and regional cerebral function in Alzheimer's disease: a SPECT blood flow study. J. Psychiatr. Res. 30 (2), 109–126.

**Bunce, D., 2001. The locus of age × health-related physical fitness interactions in serial choice responding as a function of task complexity: central processing or motor function? Exp. Aging Res. 27, 103–122.

**Bunce, D., Birdi, K., 1998. Age and physical fitness as predictors of serial choice responding: the influence of task demands and motor function. Appl. Cogn. Psychol. 12, 21–34.

**Bunce, D.J., Warr, P.B., Cochrane, T., 1993. Blocks in choice responding as a function of age and physical fitness. Psychol. Aging 8 (1), 26–33.

Carroll, J.B., 1993. Human Cognitive Abilities: A Survey of Factor-Analytic Studies. Cambridge Univ. Press, New York.

Chodzko-Zajko, W.J., Moore, K.A., 1994. Physical fitness and cognitive functioning in aging. Exerc. Sport Sci. Rev. 22, 195–220.

*Chodzko-Zajko, W.J., Schuler, P., Solomon, J., Heinl, B., Ellis, N.R., 1992. The influence of physical fitness on automatic and effortful memory changes in aging. Int. J. Aging Hum. Dev. 35, 265–285.

Cochran, W.G., 1954. The combination of estimates from different experiments. Biometrics 10, 101–129.

Cohen, J., 1992. A power primer. Psychol. Bull. 112 (1), 155–159.

Colcombe, S., Kramer, A.F., 2003. Fitness effects on the cognitive function of older adults: a meta-analytic study. Psychol. Sci. 14 (2), 125–130.

Colcombe, S.J., Erickson, K.I., Raz, N., Webb, A.G., Cohen, N.J., McAuley, E., Kramer, A.F., 2003. Aerobic fitness reduces brain tissue loss in aging humans. J. Gerontol., Ser. A, Biol. Sci. Med. Sci. 58, 176–180.

*Cosky, A.C., 1989. The effect of aerobic exercise on fitness status, cognition, and health locus of control in older women. Doctoral Dissertation, Adult and Continuing Education, Northern Illinois University, DeKalb, IL.

Dunn, A.L., Trivedi, M.H., Kampert, J.B., Clark, C.G., Chambliss, H.O., 2002. The DOSE study: a clinical trial to examine efficacy and dose response of exercise as treatment for depression. Control. Clin. Trials 23 (5), 584–603.

*Dustman, R.E., Ruhling, R.O., Russell, E.M., Shearer, D.E., Bonekat, H.W., Shigeoka, J.W., Wood, J.S., Bradford, D.C., 1984. Aerobic exercise training and improved neuropsychological function of older individuals. Neurobiol. Aging 5, 35–42.

*Dustman, R.E., Emmerson, R.Y., Ruhling, R.O., Shearer, D.E., Steinhaus, L.A., Johnson, S.C., Bonekat, H.W., Shigeoka, J.W., 1990. Age and fitness effects on EEG, ERPs, visual sensitivity, and cognition. Neurobiol. Aging 11, 193–200.

Dustman, R.E., Emmerson, R., Shearer, D., 1994. Physical activity, age, and cognitive-neuropsychological function. J. Aging Phys. Act. 2 (2), 143–181.

*El-Naggar, A.M., 1986. Physical training effect on relationship of physical, mental, and emotional fitness in adult men. J. Hum. Ergol. 15, 79–84.

*Elsayed, M., Ismail, A.H., Young, R.J., 1980. Intellectual differences of adult men related to age and physical fitness before and after an exercise program. J. Gerontol. 35 (3), 383–387.

*Emery, C.F., 1994. Effects of age on physiological and psychological functioning among COPD patients in an exercise program. J. Aging Health 6 (1), 3–16.

*Emery, C.F., Schein, R.L., Hauck, E.R., MacIntyre, N.R., 1998. Psychological and cognitive outcomes of a randomized trial of exercise among patients with chronic obstructive pulmonary disease. Health Psychol. 17 (3), 232–240.

*Emery, C.F., Shermer, R.L., Hauck, E.R., Hsiao, E.T., MacIntyre, N. R., 2003. Cognitive and psychological outcomes of exercise in a 1-year follow-up study of patients with chronic obstructive pulmonary disease. Health Psychol. 22 (6), 598–604.

Endres, M., Gertz, K., Lindauer, U., Katchanov, J., Schultze, J., Schrock, H., Nickenig, G., Kuschinsky, W., Dirnagl, U., Laufs, U., 2003. Mechanisms of stroke protection by physical activity. Ann. Neurol. 54 (5), 582–590.

**Era, P., Jokela, J., Heikkinen, E., 1986. Reaction and movement times in men of different ages: a population study. Percept. Mot. Skills 63, 111–130.

*Etnier, J.L., Berry, M., 2001. Fluid intelligence in an older COPD sample after short- or long-term exercise. Med. Sci. Sports Exerc. 33 (10), 1620–1628.

Etnier, J.L., Landers, D.M., 1998. Motor performance and motor learning as a function of age and fitness. Res. Q. Exerc. Sport 69 (2), 136–146.

Etnier, J.L., Salazar, W., Landers, D.M., Petruzzello, S.J., Han, M., Nowell, P., 1997. The influence of physical fitness and exercise upon cognitive functioning: a meta-analysis. J. Sport Exerc. Psychol. 19 (3), 249–277.

**Etnier, J.L., Johnston, R., Dagenbach, D., Pollard, R.J., Rejeski, W.J., Berry, M., 1999. The relationships among pulmonary function, aerobic fitness, and cognitive functioning in older COPD patients. Chest 116, 953–960.

*Fabre, C., Chamari, K., Mucci, P., Masse-Biron, J., Prefaut, C., 2002. Improvement of cognitive function by mental and/or individualized aerobic training in healthy elderly subjects. Int. J. Sports Med. 23, 415–421.

*Hansen, A.L., Johnsen, B.H., Sollers III, J.J., Stenvik, K., Thayer, J.F., 2004. Heart rate variability and its relation to prefrontal cognitive function: the effects of training and detraining. Eur. J. Appl. Physiol. 93, 263–272.

*Harma, M.I., Ilmarinen, J., Knauth, P., Rutenfranz, J., Hanninen, O., 1988. Physical training intervention in female shift workers. 2. The effects of intervention on the circadian rhythms of alertness, short-term-memory, and body-temperature. Ergonomics 31 (1), 51–63.

*Hascelik, Z., Basgoze, O., Turker, K., Narman, S., Ozker, R., 1989. The effects of physical training on physical fitness tests and auditory and visual reaction times of volleyball players. J. Sports Med. Phys. Fitness 29 (3), 234–239.

*Hassmen, P., Ceci, R., Backman, L., 1992. Exercise for older women: a training method and its influences on physical and cognitive performance. Eur. J. Appl. Physiol. Occup. Physiol. 64, 460–466.

Hedges, L.V., Olkin, I., 1985. Statistical Methods for Meta-Analysis. Academic Press, New York.

Higgins, J.P.T., Thompson, S.G., 2002. Quantifying heterogeneity in a meta-analysis. Stat. Med. 21 (11), 1539–1558.

Higgins, J.P., Thompson, S.G., 2004. Controlling the risk of spurious findings from meta-regression. Stat. Med. 23 (11), 1663–1682.

Higgins, J.P., Thompson, S.G., Deeks, J.J., Altman, D.G., 2003. Measuring inconsistency in meta-analyses. Br. Med. J. 327, 557–560.

*Hill, R.D., Storandt, M., Malley, M., 1993. The impact of long-term exercise training on psychological function in older adults. J. Gerontol. 48 (1), P12–P17.

*Hillman, C.H., Weiss, E.P., Hagberg, J.M., Hatfield, B.D., 2002. The relationship of age and cardiovascular fitness to cognitive and motor processes. Psychophysiology 39 (3), 303–312.

Hunter, J.E., Schmidt, F.L., 1990. Methods of Meta-Analysis: Correcting Error and Bias in Research Findings. Sage, Newbury Park, CA, pp. 512–513.

*Ismail, A.H., El-Naggar, A.M., 1981. Effect of exercise on cognitive processing in adult men. J. Hum. Ergol. 10, 83–91.

**Izquierdo-Porrera, A.M., Waldstein, S.R., 2002. Cardiovascular risk factors and cognitive function in African Americans. J. Geront., B Psychol. Sci. Soc. Sci. 57B (4), P377–P380.

*Khatri, P., Blumenthal, J.A., Babyak, M.A., Craighhead, W.E., Herman, S., Baldewicz, T., Madden, D.J., Doraiswamy, M., Waugh, R., Krishnan, K.R., 2001. Effects of exercise training on cognitive functioning among depressed older men and women. J. Aging Phys. Act. 9, 43–57.

*Kozora, E., Tran, Z.V., Make, B., 2002. Neurobehavioral improvement after brief rehabilitation in patients with chronic obstructive pulmonary disease. J. Cardiopulm. Rehabil. 22, 426–430.

Kramer, A.F., Hahn, S., Cohen, N.J., Banich, M.T., McAuley, E., Harrison, C.R., Chason, J., Vakil, E., Bardell, L., Boileau, R.A., Colcombe, A., 1999. Ageing, fitness and neurocognitive function. Nature 400, 418–419.

*Kramer, A.F., Hahn, S., McAuley, E., Cohen, N.J., Banich, M.T., Harrison, C., Chason, J., Boileau, R.A., Bardell, L., Colcombe, A., Vakil, E., 2002. Exercise, aging, and cognition: healthy body, healthy mind? In: Rogers, W.A., Fisk, A.D. (Eds.), Human Factors Interventions for the Health Care of Older Adults. Lawrence Erlbaum, Mahwah, NJ, pp. 91–120.

Lau, J., Ioannidis, J.P.A., Schmid, C.H., 1998. Summing up evidence: one answer is not always enough. Lancet 351 (9096), 123–127.

Lezak, M.D., Howieson, D.B., Loring, D.W., 2004. Neuropsychological Assessment. Oxford Univ. Press, New York.

**Lord, S.R., Menz, H.B., 2002. Physiologic, psychologic, and health predictors of 6-minute walk performance in older people. Arch. Phys. Med. Rehabil. 83, 907–911.

*Madden, D.J., Allen, P.A., Blumenthal, J.A., Emery, C.F., 1989. Improving aerobic capacity in healthy older adults does not necessarily lead to improved cognitive performance. Psychol. Aging 4 (3), 307–320.

*McCrory, M.L., 1980. The effects of an exercise program on self-concept and physical fitness on Oklahoma State University commissioned peace officers. Unpublished Thesis, Oklahoma State University, Stillwater.

*Mero, A., Jaakkola, L., Komi, P.V., 1989. Neuromuscular, metabolic and hormonal profiles of young tennis players and untrained boys. J. Sports Sci. 7, 95–100.

Moss, M., Franks, M., Briggs, P., Kennedy, D., Scholey, A., 2005. Compromised arterial oxygen saturation in elderly asthma sufferers results in selective cognitive impairment. J. Clin. Exp. Neuropsychol. 27 (2), 139–150.

*Moul, J.L., Goldman, B., Warren, B., 1995. Physical activity and cognitive performance in the older population. J. Aging Phys. Act. 3, 135–145.

North, T.C., McCullagh, P., Tran, Z.V., 1990. Effect of exercise on depression. Exerc. Sport Sci. Rev. 18, 379–415.

**Offenbach, S.I., Chodzko-Zajko, W.J., Ringel, R.L., 1990. Relationship between physiological status, cognition, and age in adult men. Bull. Psychon. Soc. 28 (2), 112–114.

*Palmer, A., 1995. The effect of an aerobic exercise program on cognitive ability and creativity in senior citizens. Doctoral Dissertation, Educational Leadership, Florida State University, Jacksonville, FL.

Perico, C.A., Skaf, C.R., Yamada, A., Duran, F., Buchpiguel, C.A., Castro, C.C., Soares, J.C., Busatto, G.F., 2005. Relationship between regional cerebral blood flow and separate symptom clusters of major depression: a single photon emission computed tomography study using statistical parametric mapping. Neurosci. Lett. 384, 265–270.

*Russell, E.M., 1982. The effects of an aerobic conditioning program on reaction times of older sedentary adults. Unpublished Dissertation, University of Utah, Salt Lake City.

*Shay, K.A., Roth, D.L., 1992. Association between aerobic fitness and visuospatial performance in healthy older adults. Psychol. Aging 7 (1), 15–24.

Sibley, B.A., Etnier, J.L., 2003. The relationship between physical activity and cognition in children: a meta-analysis. Pediatr. Exerc. Sci. 15 (3), 243–256.

Sohn, J.H., Chung, S.C., Jang, E.H., 2005. 30% oxygen inhalation enhances cognitive performance through robust activation in the brain. J. Physiol. Anthropol. Appl. Hum. Sci. 24, 51–53.

*Suominen-Troyer, S., Davis, K.J., Ismail, A.H., Salvendy, G., 1986. Impact of physical fitness on strategy development in decision-making tasks. Percept. Mot. Skills 62, 71–77.

Swain, R.A., Harris, A.B., Wiener, E.C., Dutka, M.V., Morris, H.D., Theien, B.E., Konda, S., Engberg, K., Lauterbur, P.C., Greenough, W.T., 2003. Prolonged exercise induces angiogenesis and increases cerebral blood volume in primary motor cortex of the rat. Neuroscience 117, 1037–1046.

Thomas Jr., J.R., French, K.E., 1986. The use of meta-analysis in exercise and sport: a tutorial. Res. Q. Exerc. Sport 57, 196–204.

van Boxtel, M.P.J., Langerak, K., Houx, P.J., Jolles, J., 1996. Self-reported physical activity, subjective health, and cognitive performance in older adults. Exp. Aging Res. 22, 363–379.

**van Boxtel, M.P.J., Paas, F.G.W.C., Houx, P.J., Adam, J.J., Teeken, J.C., Jolles, J., 1997. Aerobic capacity and cognitive performance in a cross-sectional aging study. Med. Sci. Sports Exerc. 29 (10), 1357–1365.

Vaynman, S., Gomez-Pinilla, F., 2005. License to run: exercise impacts functional plasticity in the intact and injured central nervous system by using neurotrophins. Neurorehabil. Neural Rep. 19, 283–295.

Vaynman, S., Ying, Z., Gomez-Pinilla, F., 2004. Hippocampal BDNF mediates the efficacy of exercise on synaptic plasticity and cognition. Eur. J. Neurosci. 20 (10), 2580–2590.

*Whitehurst, M., 1991. Reaction time unchanged in older women following aerobic training. Percept. Mot. Skills 72 (1), 251–256.

*Zervas, Y., Danis, A., Klissouras, V., 1991. Influence of physical exertion on mental performance with reference to training. Percept. Mot. Skills 72, 1215–1221.

Zheng, H., Liu, Y., Li, W., Yang, B., Chen, D., Wang, X., Jiang, Z., Wang, H., Wang, Z., Cornelisson, G., Halberg, F., 2005. Beneficial effects of exercise and its molecular mechanisms on depression in rats. Behav. Brain Res. 168 (1), 47–55.

Zornetzer, S.F., 1985. Catecholamine system involvement in age-related memory dysfunction. Ann. N. Y. Acad. Sci. 444, 242–254.