Aerobic Exercise and Neurocognitive Performance: A Meta-Analytic Review of Randomized Controlled Trials

PATRICK J. SMITH, MA, JAMES A. BLUMENTHAL, PhD, BENSON M. HOFFMAN, PhD, HARRIS COOPER, PhD, TIMOTHY A. STRAUMAN, PhD, KATHLEEN WELSH-BOHMER, PhD, JEFFREY N. BROWNDYKE, PhD, AND ANDREW SHERWOOD, PhD

Objectives: To assess the effects of aerobic exercise training on neurocognitive performance. Although the effects of exercise on neurocognition have been the subject of several previous reviews and meta-analyses, they have been hampered by methodological shortcomings and are now outdated as a result of the recent publication of several large-scale, randomized, controlled trials (RCTs).

Methods: We conducted a systematic literature review of RCTs examining the association between aerobic exercise training on neurocognitive performance between January 1966 and July 2009. Suitable studies were selected for inclusion according to the following criteria: randomized treatment allocation; mean age ≥18 years of age; duration of treatment >1 month; incorporated aerobic exercise components; supervised exercise training; the presence of a nonaerobic-exercise control group; and sufficient information to derive effect size data. Results: Twenty-nine studies met inclusion criteria and were included in our analyses, representing data from 2049 participants and 234 effect sizes. Individuals randomly assigned to receive aerobic exercise training demonstrated modest improvements in attention and processing speed (g = 0.158; 95% confidence interval [CI]; 0.055–0.260; p = .003), executive function (g = 0.123; 95% CI, 0.021–0.225; p = .018), and memory (g = 0.128; 95% CI, 0.015–0.241; p = .026). Conclusions: Aerobic exercise training is associated with modest improvements in attention and processing speed, executive function, and memory, although the effects of exercise on working memory are less consistent. Rigorous RCTs are needed with larger samples, appropriate controls, and longer follow-up periods. Key words: cognitive performance, aerobic exercise, neuropsychological performance, executive function, randomized controlled trial, meta-analysis.
intervention; and 3) the issue of individual differences in response to exercise training, with a focus on baseline, pre-exercise level of cognitive functioning as a potential moderator of exercise effects (i.e., we compared individuals with MCI to cognitively intact samples), as well as the age of study participants.

METHODS

To determine the effects of aerobic exercise interventions on neurocognitive status, an extensive literature search was conducted, using the following databases between January 1966 and July 2009: MEDLINE, PubMed, EMBASE, Gateway, CENTRAL, PsycINFO, Dissertation Abstracts International, Educational Research in Completion (ERIC), Sports Discus, Cochrane Register, PEDRO, Ageline, and CINAHL. The following search terms were used: cognitive, cognitive performance, age, elderly, mental performance, and physical activity. Additional titles were identified by a manual search of relevant journals and by identification of references included in previous meta-analyses. Unpublished dissertations and conference papers were also obtained, when possible.

Suitable studies were selected for inclusion according to the following criteria: 1) randomized treatment allocation; 2) mean age ≥18 years of age and nondemented; 3) duration of treatment >1 month; 4) involved aerobic exercise training (e.g., brisk walking, biking, or jogging). Age 18 years was selected as a lower age limit to control for development age differences in cortical thickness and myelination, which stabilize around the second decade of life (37). Studies utilizing walking interventions that were not aerobic were not included (e.g., slow walking with frequent breaks) to ensure that included trials incorporated some aerobic exercise component. Additional inclusion criteria included: 5) the presence of a control group that did not engage in aerobic exercise; and 6) sufficient information to derive an estimate of effect size (ES).

After initial identification and retrieval of studies, several were found to be quasirandomized studies (36) or used case-control methodologies (15,36,38–44), were of insufficient duration to include (45–47), were found not to be nonrandomized based on personal communication with the trial’s principal investigator (36), or did not utilize a nonaerobic exercise control group (48,49). Another trial was conducted among adolescents and was, therefore, excluded (50). Several trials utilized “dual-task” interventions (e.g., walking and talking) (51–53) or balance and strength-training (54,55) and were, therefore, not included as it could not be ascertained whether exercise was of sufficient intensity to produce aerobic changes. Several trials were not included because they utilized physical activity interventions with exclusively nonaerobic exercise components among individuals with dementia (52,56–65). The few studies utilizing walking interventions were either explicitly nonaerobic (58) or allowed residents with limited mobility (e.g., walking) to rest as needed (52), thereby limiting their generalizability to more healthy samples. Accordingly, these studies were excluded from the current analyses. For two trials in which the method of randomization was unclear (39,66), we attempted to contact the respective authors and were able to confirm that one trial followed a true randomization scheme (39). Results were unchanged when the remaining study was excluded and we, therefore, included this trial in all analyses (66).

Assessment of Study Quality

Two raters (P.J.S., B.M.H.) independently extracted information from each article, using an identical review protocol, which included study identifiers (e.g., authors’ names, year of publication, publishing journal), duration of treatment, intensity of exercise, modality of exercise, binding of assessment personnel to treatment status, during assessments, intention-to-treat (ITT) analyses, and time of follow-up assessment. ESs were assessed independently. Interrater reliability was assessed for the outcome domains in question (i.e., in each cognitive domain as well as for study characteristics). For all areas, interrater reliability was found to be excellent ($r > .90$; Cohen’s $\kappa = 0.75$).

RESULTS

Neuropsychological test results were classified according to the cognitive domains described by Lezak and colleagues (67). We considered neurocognitive tests that could be classified in the following categories: attention and processing speed (the sustained focus of cognitive resources with selective concentration and rapid processing of information (67,68), executive function (a set of cognitive skills responsible for the planning, initiation, sequencing, and monitoring of complex, goal-directed behavior), working memory (short-term storage and manipulation of information), and declarative memory (retention, recollection, and recognition of previously encountered information, hereafter referred to only as “memory”). We considered including “complex processing speed” as a measure of executive function as in previous analyses (9), but results were unchanged regardless of the classification of this test.

Analyses were conducted, using Comprehensive Meta Analysis software (Biostat, Englewood, New Jersey). Data were analyzed, using both fixed and random effects models and Cohen’s $G$ for between-group differences (69). Fixed effects analysis assumes that all studies are drawn from the same population, such that differences in treatment effects across studies are attributed to sampling and methodological variability (i.e., error variance). In contrast, random effects analysis allows for the possibility that studies are drawn from different populations, such that differences across studies may be due to unidentified sources of variation and provides a more conservative estimate of treatment effects (70). However, because results did not differ between fixed and random effects analyses and because random effects are generally recommended for examining treatment effects in meta-analytic studies (70), we have presented the random effects findings only. In trials reporting multiple effect sizes within the same neurocognitive domain, data were collapsed by averaging all ESs within each neurocognitive domain for each study, such that each study produced no more than one ES per domain. For the purposes of the study quality analyses, treatment effects were collapsed for each study for all neurocognitive domains. In addition, two trials in our literature search produced multiple publications in either peer-reviewed journals (71–73) or book chapters (74,75) that were combined for the purposes of analysis. Homogeneity of treatment effects was assessed, using the Q statistic. Three trials collected neurocognitive data at multiple time points in which participants continued to receive treatment (30,73,76). However, in only one study were the effects of treatment uncontaminated by crossover between groups (30). For this study only (30), we chose data from the longest follow-up assessment for inclusion in our analyses, although results were unchanged when other time points were examined.

Exploratory sensitivity analyses (77,78) were conducted to investigate sample characteristics that may have moderated the effects of treatment on neurocognitive outcomes. Specifically, three trial characteristics were examined: duration, intensity, and mode of exercise intervention. We also examined two important methodological characteristics associated with methodological quality: blinding of assessors of neurocognitive outcomes and use of ITT analyses. As an additional analysis, we examined whether treatment effects varied by cognitive status of participants at baseline (i.e., “nonimpaired” or MCI; patients with dementia [Alzheimer’s disease] were excluded) and age of study participants.

Our initial literature search yielded 5538 potentially relevant studies, 68 of which were retrieved for full-text review. Twenty-nine studies incorporating data from 2049 participants met inclusion criteria and were included in the present analyses (Table 1), including data for 1024 experimental participants and 997 controls. Two hundred thirty-four ESs were available for analysis. Trials ranged in duration from 6 weeks (79) to 18 months (30). As shown in Table 1, the primary exercise modality was brisk walking and/or jogging and control groups were typically assigned to a wait-list control, although
TABLE 1. Randomized Controlled Trials Examining the Effect of Aerobic Exercise on Neurocognitive Function

<table>
<thead>
<tr>
<th>Author / Year</th>
<th>Sample</th>
<th>Intervention</th>
<th>Instruments</th>
<th>Methodological Characteristics</th>
<th>Hedge's G</th>
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<tbody>
<tr>
<td>Bakken, 2001 (103)</td>
<td>15, older adults, ages 72 to 91</td>
<td>Duration: 8 wks Frequency: 3 min, 3/wk Intensity: - - Combined Strength Training: Y MCI: N</td>
<td>Imaging (Verbal Fluency), Visual Discrimination, Raven’s Progressive Matrices, Short-Term Retention, Addition, Perception of Ambiguous Stimuli</td>
<td>Attrition: 0% Blinding: N</td>
<td>AT = .169</td>
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<tr>
<td>Emery, 1998 (111)</td>
<td>79, with stable COPD, age range not reported M = 67</td>
<td>Duration: 10 wks Frequency: 45 min, 3/wk Intensity: - - Combined Strength Training: Y MCI: N</td>
<td>Verbal Fluency, Digit Vigilance, Finger Tapping, TMT-A, TMT-B, Digit Symbol</td>
<td>Attrition: 5% ITT: N Blinding: N</td>
<td>AT = .075</td>
</tr>
<tr>
<td>Fabre, 2002 (112)</td>
<td>32, healthy elderly adults, ages 60 to 76</td>
<td>Duration: 8 wks Frequency: 45 min, 2/wk Intensity: - - Combined Strength Training: N MCI: N</td>
<td>Wechsler Memory Scale</td>
<td>Attrition: 0% ITT: N Blinding: N</td>
<td>EX = −.188</td>
</tr>
<tr>
<td>Kramer, 1999 &amp; 2002 (74, 75)</td>
<td>124, sedentary, ages 60 to 75</td>
<td>Duration: 26 wks Frequency: 40 min, 3/wk Intensity: 50–70% HRR Combined Strength Training: N MCI: N</td>
<td>Reaction Time Tests: Switching Trials, Non-Switching Trials, Incompatible Trials, Compatible Trials, Interference Effect (Difference Between Compatible Trials and Incompatible Trials), Stop Signal Trials, Simple Reaction-Time Trials</td>
<td>Attrition: 29% ITT: N Blinding: N</td>
<td>AT = .091</td>
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TABLE 1. Continued

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<tr>
<th>Author/Year</th>
<th>Sample Description</th>
<th>Intervention Details</th>
<th>Instruments</th>
<th>Methodological Characteristics</th>
<th>Hedge’s G</th>
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<tbody>
<tr>
<td>Lautenschlager, 2008 (30)</td>
<td>170, elderly adults with MCI, age M = 69</td>
<td>Duration: 72 wks* Frequency: 50 min, 3/wk Intensity: - - Combined Strength Training: N MCI: Y</td>
<td>Word list recall (immediate and delayed), Digit Symbol, COWAT</td>
<td>Attrition: 19% ITT: Y Blinding: Y</td>
<td>AT = -.083 EX = -.071 ME = .322**</td>
</tr>
<tr>
<td>Masley, 2008 (114)</td>
<td>56, adults, age M = 45</td>
<td>Duration: 10 wks Frequency: 5/wk Intensity: 70–85% MHR Combined Strength Training: Y MCI: N</td>
<td>CNS Vital Signs (verbal memory, symbol digit coding, the Stroop test, shifting attention, continuous performance)</td>
<td>Attrition: 16% ITT: N Blinding: N (computerized)</td>
<td>AT = -.158 EX = .487‡ ME = .351</td>
</tr>
<tr>
<td>Oken, 2004 (117)</td>
<td>69, multiple sclerosis, M = 49</td>
<td>Duration: 26 wks Frequency: 90 min, 1/wk Intensity: - - Combined Strength Training: N MCI: N</td>
<td>Stroop Color-Word test, Simple Reaction Time, Complex Reaction Time, Attentional Shift Task, PASAT, Logical Memory, WAIS Similarities</td>
<td>Attrition = 12% ITT: N Blinding: Y</td>
<td>AT = .074 EX = .133 WM = -.354 ME = .000</td>
</tr>
<tr>
<td>Oken, 2006 (118)</td>
<td>135, healthy adults, ages 65 to 85</td>
<td>Duration: 26 wks Frequency: 60 min, 1/wk Intensity: 70% HRR Combined Strength Training: N MCI: N</td>
<td>Stroop Interference, Word List Recall, Letter-Number Sequencing, Covert Orienting, Divided Attention, Set Shifting, Simple Reaction time, Complex Reaction time</td>
<td>Attrition = 13% ITT: N Blinding: Y</td>
<td>AT = -.132 EX = -.034 WM = -.029 ME = -.055</td>
</tr>
<tr>
<td>Okumiya, 1996 (29)</td>
<td>42, healthy older adults, ages 75 to 87</td>
<td>Duration: 24 wks Frequency: 60 min, 3/wk Intensity: - - Combined Strength Training: Y MCI: N</td>
<td>MMSE, Hasegawa Dementia Scale, Visuospatial Cognitive Performance Test</td>
<td>Attrition: 0% ITT: N Blinding: N</td>
<td>AT = .938**</td>
</tr>
<tr>
<td>Panton, 1990 (119)</td>
<td>39, healthy untrained older adults, ages 70 to 79</td>
<td>Duration: 26 wks Frequency: 45 min, 3/wk Intensity: 75% HRR Combined Strength Training: N MCI: N</td>
<td>-</td>
<td>Attrition: 14% ITT: N Blinding: N</td>
<td>AT = .111</td>
</tr>
<tr>
<td>Perri, 1984 (121)</td>
<td>42, healthy older adults, ages 60 to 79</td>
<td>Duration: 15 wks Frequency: 30 min, 3/wk Intensity: 40–50% HRR Combined Strength Training: N MCI: N</td>
<td>Rey Auditory Verbal Learning Task</td>
<td>Attrition: 41% ITT: N Blinding: N</td>
<td>ME = .261</td>
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<tr>
<td>Russell, 1982 (122)</td>
<td>45, sedentary older adults, ages 55 to 70</td>
<td>Duration: 16 wks&lt;br&gt;Frequency: 45 min, 3/wk&lt;br&gt;Intensity: ---&lt;br&gt;Combined Strength Training: N&lt;br&gt;MCI: N</td>
<td>Simple Reaction Time, Complex Reaction Time&lt;br&gt;Attrition: 4%&lt;br&gt;ITT: N&lt;br&gt;Blinding: N</td>
<td>AT = .214&lt;br&gt;EX = .081</td>
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<td>Scherder, 2005 (79)</td>
<td>43, elderly adults with MCI, ages 76 to 94</td>
<td>Duration: 6 wks&lt;br&gt;Frequency: 30 min, 3/wk&lt;br&gt;Intensity: ---&lt;br&gt;Combined Strength Training: N&lt;br&gt;MCI: Y</td>
<td>Category Naming, TMT-A, TMT-B, Digit Span, Visual Memory Span, Rivermead Behavioral Memory Test (Faces and Pictures), Verbal Learning and Memory Test: Direct Recall, Delayed Recall, and Recognition&lt;br&gt;Attrition: 7%&lt;br&gt;ITT: N&lt;br&gt;Blinding: Y</td>
<td>EX = .441&lt;br&gt;WM = .037&lt;br&gt;ME = .413</td>
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<td>Stroth, 2009 (124)</td>
<td>28, young adults, age M = 20</td>
<td>Duration: 6 wks&lt;br&gt;Frequency: 30 min, 3/wk&lt;br&gt;Intensity: 70–100% aerobic threshold&lt;br&gt;Combined Strength Training: N&lt;br&gt;MCI: N</td>
<td>Digit Symbol Substitution Test, Rey Auditory Verbal Learning Test, Stroop Test&lt;br&gt;Attrition: 22%&lt;br&gt;ITT: N&lt;br&gt;Blinding: Y</td>
<td>AT = -.123&lt;br&gt;ME = .650‡</td>
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<td>Wallman, 2004 (125)</td>
<td>61, adults with chronic fatigue syndrome, ages 16 to 74</td>
<td>Duration: 12 wks&lt;br&gt;Frequency: increased progressively Intensity: based on target HR from treadmill testing&lt;br&gt;Combined Strength Training: N&lt;br&gt;MCI: N</td>
<td>Stroop Test (82 questions) Stroop Test (95 questions)&lt;br&gt;Attrition: 10%&lt;br&gt;ITT: N&lt;br&gt;Blinding: Y</td>
<td>EX = .479*</td>
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<td>Whitehurst, 1991 (126)</td>
<td>14, sedentary older women, ages 61 to 73</td>
<td>Duration: 8 wks&lt;br&gt;Frequency: 35 min, 3/wk&lt;br&gt;Intensity: ---&lt;br&gt;Combined Strength Training: N&lt;br&gt;MCI: N</td>
<td>Simple Reaction Time, Choice Reaction Time&lt;br&gt;Attrition: 0%&lt;br&gt;ITT: N&lt;br&gt;Blinding: N</td>
<td>AT = -.551&lt;br&gt;EX = -.609</td>
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<td>Williams, 1997 (104)</td>
<td>187, all women, age M = 72</td>
<td>Duration: 42 wks&lt;br&gt;Frequency: 35 min, 2/wk&lt;br&gt;Intensity: ---&lt;br&gt;Combined Strength Training: Y&lt;br&gt;MCI: N</td>
<td>Digit Span, Picture Arrangement, Cattell’s Matrices&lt;br&gt;Attrition: 20%&lt;br&gt;ITT: N&lt;br&gt;Blinding: N</td>
<td>AT = .501**&lt;br&gt;EX = .189&lt;br&gt;WM = .348*</td>
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<td>Williamson, 2009 (34)</td>
<td>102, elderly adults, ages 70–89 years</td>
<td>Duration: 52 wks&lt;br&gt;Frequency: 45 min, 1–2/wk&lt;br&gt;Intensity: ---&lt;br&gt;Combined Strength Training: Y&lt;br&gt;MCI: N</td>
<td>Digit Symbol, Modified Stroop Test, 3MSE, Rey Auditory Verbal Learning Test&lt;br&gt;Attrition: 10%&lt;br&gt;ITT: N&lt;br&gt;Blinding: Y</td>
<td>AT = .206&lt;br&gt;EX = .026&lt;br&gt;ME = .011</td>
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<tr>
<td>van Uffelen, 2008 (33)</td>
<td>152, elderly adults with MCI, age M = 75</td>
<td>Duration: 52 wks&lt;br&gt;Frequency: 60 min, 2/wk&lt;br&gt;Intensity: &gt;3 METs&lt;br&gt;Combined Strength Training: N&lt;br&gt;MCI: Y</td>
<td>Digit Symbol, Stroop Color Word Test, Verbal Fluency, Auditory Verbal Learning Test&lt;br&gt;Attrition: 9%&lt;br&gt;ITT: Y&lt;br&gt;Blinding: Y</td>
<td>AT = -.10&lt;br&gt;EX = -.04&lt;br&gt;ME = -.03</td>
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*** p < .001; ** p < .01; * p < .05; ‡ p < .10; AT = attention and processing speed; EX = executive function; MET = metabolic equivalent, WM = working memory; MCI = Mild Cognitive Impairment, ME = memory; HRR = Heart Rate Reserve; MHR = maximum heart rate; RPE = Ratings of Perceived Exertion; TMT = Trail Mating Test; ¥ indicates multiple time points of data.
stretching and toning, health education, and relaxation exercises were also used. Rates of attrition varied widely (range, 0%–41%; mean attrition, 12.2%). Only 13 (44.8%) studies utilized blinded assessments and only seven (24.1%) studies utilized ITT analyses. The effects of exercise on individual neurocognitive measures are presented in Table 2. Due to the substantial number and heterogeneity of neurocognitive tests (Table 3), only those tests used in more than one study are presented.

### Attention and Processing Speed

Twenty-four studies examined the effects of aerobic exercise on attention and processing speed. Exercise training was...
associated with modest improvements in attention and processing speed \((g = 0.158; 95\% \text{ confidence interval [CI]}, 0.055–0.260; p = .003)\) (Fig. 1) and this effect was consistent across studies \((Q_{23} = 26.249, p = .289)\). Moderator analyses demonstrated that trials of greater duration did not improve attention and processing speed to a greater extent than briefer interventions \((r = .17, Q_{1} = 3.555, p = .399)\). Similarly, intensity was not associated with variations in attention and processing speed outcomes \((r = -.375, Q_{1} = 1.41, p = .225)\). Results did not differ between individuals with MCI \((g = 0.028, p < .001)\) and other samples \((g = 0.181, p = .825)\) \((Q_{1} = 1.228, p = .268)\). Combined interventions improved attention and processing speed to a greater extent \((g = 0.350; 95\% \text{ CI}, 0.042–0.658; p = .026)\) than aerobic only interventions \((g = 0.098; 95\% \text{ CI}, -0.012 to 0.208; p = .152)\) \((Q_{1} = 4.373, p = .037)\). There was no observed association between the mean age of study participants and improvements in attention and processing speed \((r = -.047, p = .817)\).

### Executive Function

Nineteen studies assessed the effects of aerobic exercise on executive function. Aerobic exercise was associated with modest improvements in executive function \((g = 0.123; 95\% \text{ CI}, 0.021–0.225; p = .018)\) (Fig. 2), and effects were of similar magnitude across studies \((Q_{18} = 13.418, p = .766)\). Neither duration \((r = -.436, Q_{1} = 3.627, p = .057)\) nor intensity \((r = -.203, Q_{1} = 0.413, p = .520)\) were related to improved executive function. Improvements in executive function were smaller among individuals with MCI \((g = -0.004, p = .973)\) relative to other samples \((g = 0.153, p = .008)\) \((Q_{1} = 1.377, p = .241)\), and findings did not differ between studies that included only aerobic exercise \((g = 0.109, p = .074)\) or combined aerobic exercise with other exercises \(\text{e.g.},\) strength training \((g = 0.163, p = .106)\) \((Q_{1} = 0.214, p = .644)\). Finally, there was no observed association between the mean age of study participants and improvements in executive function \((r = -.348, p = .130)\).

### Working Memory

Twelve studies examined the effects of aerobic exercise on working memory. Exercise did not seem to improve working memory performance \((g = 0.032; 95\% \text{ CI}, -0.103 to 0.166; p = .642)\) (Fig. 3) and this effect was relatively consistent across trials \((Q_{11} = 12.241, p = .346)\). Similar to other cognitive domains, neither the duration of the intervention \((r = .346, Q_{1} = 1.438, p = .230)\) nor the intensity of exercise \((r = .109, Q_{1} = 0.123, p = .725)\) seemed to moderate the effects of treatment. Only one study examined the effects of working memory among individuals with MCI and test for moderation was, therefore, not examined. Combined interventions \((n = 2)\) seemed to improve working memory \((Q_{1} = 4.817, p = .028)\) \((g = 0.288; 95\% \text{ CI}, 0.030–0.546; p = .028)\) relative to aerobic only interventions \((g = -0.042; 95\% \text{ CI}, -0.184 to 0.101; p = .567)\).
addition, a significant association was observed between mean age of study participants and improvements in working memory, with older samples demonstrating greater improvements relative to younger samples ($r = .564$, $p = .051$).

### Memory

Sixteen studies assessed the effects of aerobic exercise on memory function. Aerobic exercise was associated with modest improvements in memory relative to controls ($g = 0.128$; 95% CI, $-1.00$ to $1.00$; $p = .018$). Each study is denoted with a circle, with larger sample sizes corresponding to larger marks.
AERobic exercise and neurocognition

**DISCUSSION**

Results indicate that aerobic exercise training confers modest improvements in neurocognitive function among healthy older adults, including improvements in attention and processing speed, executive function, and memory. Aerobic exercise did not seem to benefit working memory, however. Moderator analyses demonstrated that studies utilizing combined aerobic exercise and strength training interventions improved attention and processing speed and working memory to a greater extent than aerobic exercise alone. In addition, we found preliminary evidence that trials among individuals with MCI may be associated with greater improvements in memory relative to those among noncognitively compromised samples. In contrast, neither training characteristics, such as study duration and intensity, nor methodological quality were associated with differential improvements in neurocognition.

Although previous meta-analytic reviews have reported that exercise may improve neurocognitive performance (8–12,32), ours is one of the largest reviews to date demonstrating that aerobic exercise improves neurocognition among nondemented adults and the first to show that physical activity may enhance memory performance among individuals with MCI, a group at elevated risk for Alzheimer’s disease (24). Several previous meta-analytic studies have examined the relationship between physical activity and cognitive function (8–12,32). Colcombe and Kramer (9) reported that RCTs of exercise are associated with clinically meaningful improvements in executive function, processing speed, memory, and motor function. Our findings showed markedly weaker effects relative to this review, most likely as a result of excluding two decidedly positive studies trials included in the meta-analysis of Colcombe and Kramer (35,36) which, on closer examination, were not truly RCTs. In a Cochrane review, Angevaren and colleagues (11) concluded that,
although RCTs of aerobic exercise among individuals without cognitive impairment were associated with modest improvements in attentional processes, cognitive speed, and motor function, the existing data were insufficient to show that improvements in cognition were attributable to changes in cardiovascular fitness. Similarly, Etnier and colleagues (32) have demonstrated that, although higher levels of fitness were associated with better neurocognitive performance among young adults, cross-sectional study designs, studies examining pre and post comparisons found that larger gains in aerobic fitness were associated with lesser improvements in cognitive performance (32). Etnier and colleagues (8) have also noted that methodological limitations contributed to significant variability in treatment effects, with higher-quality studies tending to show smaller effects, and studies with the highest-quality rating demonstrating no effect of exercise on neurocognition. Most recently, van Uffelen and colleagues (12) reported that physical activity interventions among individuals without cognitive decline, on average, tended to report improved neurocognitive function. However, van Uffelen and colleagues (12) did not attempt to statistically combine treatment ESs across studies, reported that the majority of existing trials examining this question have failed to demonstrate a treatment benefit, and found that the extant literature is marked by a lack of high-quality studies. The present analyses address many of the issues raised by this previous review by including several large, high-quality RCTs not previously incorporated in systematic literature syntheses (30,31,33,34).

The finding that exercise may produce larger improvements in memory for individuals with MCI than other patient groups is novel and warrants further investigation, although this must be viewed as preliminary. Although Heyn and colleagues (10) demonstrated that physical activity is associated with improvements in mental status among individuals with dementia, the majority of these trials were conducted among institutionalized adults with dementia and utilized balance and isometric exercises and did not examine the effects of aerobic exercise, specifically, on neurocognition. The finding that aerobic exercise improves memory is consistent with several animal studies, which have indicated that physical activity and cardiovascular health may take years to affect brain health (106,107). In addition, RCTs that have demonstrated that cerebral alterations associated with inflammation (101,102), although these relationships have yet to be investigated.

The present meta-analysis has several limitations. First, the literature is marked by a lack of high-quality trials examining the effects of aerobic exercise on cognitive end points. Trials included in our analyses differed substantially in their use of blinded evaluations, ITT analyses, and clinically validated cognitive assessment tools. Second, RCTs are limited by logistical constraints in their ability to sustain interventions over prolonged periods of time. Accordingly, the majority of studies examining cognitive end points have done so after several months of aerobic training (79,103) or, in some instances, incorporated follow-ups several years later (33,104). There are limited data regarding how physical activity sustained over the course of several years may affect cognitive end points (2,105), despite observational data indicating that physical activity and cardiovascular health may take years to affect brain health (106,107). In addition, RCTs that have examined the neurocognitive effects of aerobic exercise over an extended time period have demonstrated greater improvements in memory over longer follow-up periods (30,73). Third, the majority of extant studies have utilized interven-
AEROBIC EXERCISE AND NEUROCOGNITION

tions with frequency and intensity prescribed in accordance with the American Heart Association recommendations for cardiac rehabilitation (i.e., heart rates at 70% peak oxygen consumption three times per week). It is, therefore, possible that there was not enough of a range in exercise prescriptions to observe an effect on neurocognition. Finally, there is a lack of consensus as to which neurocognitive measures are most appropriate to examine changes in neurocognitive function associated with exercise. As shown in Table 2, there is substantial heterogeneity in treatment effects among neurocognitive measures. Accordingly, future studies would benefit from the identification of a standardized neurocognitive battery with the appropriate psychometric characteristics to examine neurocognitive measures associated with aerobic exercise.

In conclusion, aerobic exercise training results in modest improvements in cognitive performance among nondemented adults. Trials utilizing longer interventions were associated with greater gains in attention and processing speed, whereas trials conducted among individuals with MCI tended to demonstrate greater improvements in memory relative to non-MCI samples. Additional randomized trials are needed with larger samples, more extensive follow-up periods, appropriate controls, and more extensive measurement of potential mediators of cognitive change. Accordingly, future studies would benefit from the assessment of subclinical vascular health as a potential mediator of the exercise and neurocognition relationship, as this has been associated with improvements in aerobic capacity (100) and neurocognitive performance in other samples (108,109). Future studies should also collect functional magnetic resonance imaging or diffusion tensor imaging measures to track cerebral alterations post exercise, as several previous studies have demonstrated that exercise and improved fitness may increase cerebral blood flow (16) and alter blood oxygen level dependent response patterns to cognitive tasks (89), as well as improve structural brain health, such as by increasing white (88) and gray matter integrity (22) and brain volume (88). Finally, more rigorous studies should examine the effects of aerobic exercise training among individuals with MCI to determine whether this is a plausible strategy to delay or prevent incident dementia (101).

REFERENCES

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