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Review

The effects of acute exercise on cognitive performance: A meta-analysis

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ABSTRACT

There is a substantial body of literature related to the effects of a single session of exercise on cognitive performance. The premise underlying this research is that physiological changes in response to exercise have implications for cognitive function. This literature has been reviewed both narratively and meta-analytically and, although the research findings are mixed, researchers have generally concluded that there is a small positive effect. The purpose of this meta-analysis was to provide an updated comprehensive analysis of the extant literature on acute exercise and cognitive performance and to explore the effects of moderators that have implications for mechanisms of the effects. Searches of electronic databases and examinations of reference lists from relevant studies resulted in 79 studies meeting inclusion criteria. Consistent with past findings, analyses indicated that the overall effect was positive and small ($g=0.097$ $n=1034$). Positive and small effects were also found in all three acute exercise paradigms: during exercise ($g=0.101$; 95% confidence interval [CI]; 0.041–0.160), immediately following exercise ($g=0.108$; 95% CI; 0.069–0.147), and after a delay ($g=0.103$; 95% CI; 0.035–0.170). Examination of potential moderators indicated that exercise duration, exercise intensity, type of cognitive performance assessed, and participant fitness were significant moderators. In conclusion, the effects of acute exercise on cognitive performance are generally small; however, larger effects are possible for particular cognitive outcomes and when specific exercise parameters are used.

Contents

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1. Introduction

A growing body of research has been designed to further our understanding of how a single bout of exercise (also referred to as acute exercise) affects cognitive performance. This research is based upon the premise that physiological responses to exercise have an impact on cognitive functioning which can be assessed using behavioral measures. The physiological responses that have been implicated in the cognitive literature include changes in heart rate (Allard et al., 1989; Davranche et al., 2005, 2006; Hillman et al., 2003; Kamijo et al., 2004a,b; McMorris and Graydon, 2000), levels of brain-derived neurotrophic factor (Ferris et al., 2007; Winter et al., 2007), and changes in plasma catecholamines (Chmura et al., 1994). Researchers have typically assessed the effects of acute exercise on cognition using one of three exercise paradigms: maximal intensity exercise, submaximal intensity exercise, or exercise in conjunction with hydration status. In a narrative review, Tomporowski and Ellis (1986) described this literature as being limited by a lack of consistency in methodology and by a failure to use theory-based approaches. Since then, this literature has grown and has been reviewed narratively on several occasions (Brisswalter et al., 2002; McMorris and Graydon, 2000; Tomporowski, 2003a,b). Although individual empirical studies have yielded inconsistent results, the consensus of the narrative reviewers is that there is a positive effect of acute exercise on cognitive performance (Brisswalter, et al., 2002; McMorris and Graydon, 2000; Tomporowski, 2003a,b). However, given the heterogeneity of the findings, the use of meta-analytic techniques is warranted to statistically summarize empirical findings. Meta-analysis also allows for the testing of moderating variables that may yield information regarding potential mechanisms of the effects.

The effects of acute exercise have been examined meta-analytically in three previous reviews (Etnier, et al., 1997; Lambourne and Tomporowski, 2010; Sibley and Etnier, 2003). Etnier et al. (1997) indicated that acute exercise has a significant small positive effect on cognitive performance (ES=0.16). Sibley and Etnier (2003) limited their review to studies testing the effects of acute exercise on cognitive performance in children and also reported a significant small effect (ES=0.37). However, these earlier meta-analyses have two limitations. First, numerous empirical studies on acute exercise and cognition have been conducted since the publication of these earlier reviews. Second, neither review was designed specifically to examine acute exercise; thus, moderators particularly relevant to the effects of acute exercise on cognitive performance were not examined. Thus, these early meta-analyses provided important direction for future research by establishing that acute exercise has reliable small effects on cognitive performance, but the failure to test relevant moderators means that conclusions relative to potential mechanisms of the effects could not be drawn.

More recently, Lambourne and Tomporowski (2010) conducted a meta-analytic review specifically focused on acute exercise studies (n=40), in which they included studies testing the effects in healthy young adults and measuring cognitive performance prior to exercise and then either during exercise (n=21) or following exercise (n=29). Their results indicated that exercise had a detrimental effect on cognitive performance during exercise (d=-0.14), but improved cognitive performance after exercise (d=0.20). Moderator variables particularly relevant to acute exercise were examined and included exercise intensity and duration, timing of the cognitive task administration, exercise mode, cognitive task type, and study design. Findings relevant to these moderators could provide insights as to the potential mechanisms of the effect and guidance for exercise recommendations to garner the largest cognitive benefits. However, the scope of the review was limited by the decisions to focus on young adults and to only include studies using "within-subjects, repeated measures" (Lambourne and Tomporowski, 2010, p. 14) designs. These decisions clearly impact the generalizability of the conclusions and result in the exclusion of numerous relevant studies that might contribute to our understanding of the effects of acute exercise on cognitive performance.

Thus, the purpose of this meta-analysis is to provide a more comprehensive review of the extant literature on acute exercise and cognitive performance. The use of less restrictive inclusion criteria allows for the testing of additional relevant moderators and provides a more broad review of the literature. In addition, by including participants of all ages, the effects of acute exercise for children and older adults can be explored. This may be particularly relevant because past reviews have suggested that larger effects from chronic exercise can be observed for these age groups (Angevaren et al., 2008; Colcombe and Kramer, 2003; Etnier, et al., 1997; Sibley and Etnier, 2003) and it is not known if this pattern of results would also apply to acute exercise.

Prior to testing the effects of moderators, studies in this analysis were separated into subsets based upon the three particular paradigms that were used (during exercise, immediately following exercise, and after a delay of longer than 1 min). This decision was based upon the fact that the potential underlying physiological mechanisms are affected directly by exercise and that the effects dissipate following exercise cessation. Thus, it is expected that findings for cognitive performance would differ for studies testing the effects of acute exercise on cognitive performance during exercise as compared to those testing the effects at various time points following exercise (Lambourne and Tomporowski, 2010). Four primary moderators were then examined for studies within each of these paradigms. The primary moderators were selected based upon the fact that they have been previously identified as important variables to consider when examining the effects of physical activity on cognitive performance and included exercise intensity, timing of test administration relative to exercise, cognitive task type, and initial fitness level of the participants.

Exercise intensity is a moderator that has frequently been considered in acute exercise studies. The frequent attention given to exercise intensity is due to its relevance to understanding mechanisms of the effects. The inverted-U hypothesis and drive theories both suggest that exercise intensity will influence the size of the effect. In particular, the inverted-U hypothesis predicts that moderate intensity exercise will have the greatest benefits while the drive theories suggest that the largest effects will be observed at high intensity. Clearly when considering mechanisms such as heart rate, catecholamines, and brain-derived neurotrophic factor (BDNF), the intensity level of the exercise is important for determining the amount of change in these physiological mechanisms that will be achieved and this may then be important for predicting the behavioral effects as well. As an example, studies testing the effects of acute exercise on circulating BDNF indicate that high intensity protocols result in larger increases than do low-intensity protocols (Knaepen et al., 2010). Thus, if BDNF is a mediator of the effects of acute exercise on cognitive performance, intensity would be expected to influence behavioral outcomes.

The specific timing of the cognitive test administration is a second moderator of interest. This moderator has been found to influence the effect of acute exercise on cognitive performance by young healthy adults (Lambourne and Tomporowski, 2010). This moderator also has implications for mechanisms of the effects because of the specific way in which the mechanisms are impacted by exercise. For example, exercise has transient effects on BDNF, therefore the timing of the cognitive assessment may be critical in terms of the effects mediated by BDNF.

The relationship between acute exercise and cognitive performance might also be dependent upon the nature of the cognitive task. Etnier et al. (1997) reported that acute exercise had large beneficial effects on motor skills, academic achievement, and when tested using a composite from a variety of tests (ES ranging from 1.20 to 1.47); however, it had negative effects on tasks related to reasoning and verbal skills (ES ranging from −0.06 to −0.02). At the time of Etnier et al.'s review, many acute exercise studies used reaction time tasks (Fleury and Bard, 1987; Hogervorst et al., 1996; McMorris, 1995; McMorris and Keen, 1994; Travlos and Marisi, 1995) and visual recognition tasks (Bard and Fleury, 1978; Fleury et al., 1981). Recently, researchers have begun to examine the effects of acute exercise on executive function or frontal-lobe dependent measures (Chang and Etnier, 2009a,b; Dietrich and Sparling, 2004; Sibley et al., 2006; Tomporowski et al., 2005). This may reflect interest in testing the transient hypofrontality hypothesis (Dietrich, 2006) and past meta-analytic evidence suggesting that cognitive task type moderates the effects of both acute and chronic exercise (Angevaren, et al., 2008; Colcombe and Kramer, 2003; Etnier, et al., 1997; Lambourne and Tomporowski, 2010).

A final primary moderator that is of interest is the initial fitness level of the participants (see Chodzko-Zajko, 1991; Tomporowski, 2003b; Tomporowski and Ellis, 1986). Again, this relates to the potential mechanisms of the effects. For example, some evidence suggests that the BDNF response to acute exercise is dependent upon the participants' level of training (Castellano and White, 2008; Schulz et al., 2004; Zoladz et al., 2008). Thus, if BDNF is a mediator, one might expect fitness level to moderate the behavioral effects of acute exercise.

Thus, this meta-analysis is designed to extend beyond the existing meta-analytic reviews by using broader inclusion criteria than have been used previously and by including moderators that have not been previously examined and that have

Table 1 – Cognitive tasks and cognitive task categories.

1. Information processing
a. Finger tapping
b. Visual search task
c. Stroop word or Stroop color
d. Digit symbol substitution
e Anticipation/coincident timing task
f. Rotor task
g. Tracking task
h. Draw a line task
i. Visual field
j. Wechsler Intelligence Scale for Children — coding
k. Number cancelation task
2. Reaction time
a. Simple pre-motor time
b. Choice pre-motor time
c. Simple reaction time
d. Choice reaction time
3. Attention
a. PASAT
b. Woodchuck–Johnson test of concentration
4. Crystallized intelligence
a. Addition and subtraction (Math)
b. WAIS
c. MMSE
d. Eysenck IQ: verbal
e. Eysenck's IQ: numerical ability
f. Eysenck's IQ: visuospatial
g. Kbit
5. Executive function
a. Erickson flankers task
b. Trail making test
c. Verbal fluency/word fluency
d. Decision making
e. Incompatible reaction time
f. Stroop interference
g. Alternate uses task
h. Random number generation
i. Digit span (backward)
j. Wisconsin card sorting task
k. Raven's progressive matrices
l. Math problem solving
m. Logical reasoning
6. Memory
a. Free recall
b. Visual short-term memory
c. Verbal working memory (Auditory Verbal Learning Test or California Verbal Learning Test)
d. Digit span (forward)
e. Figural learning test
f. Sequential memory
g. Paired associate

implications for mechanisms of the effects. Based upon the findings of previous meta-analyses (Etnier, et al., 1997; Lambourne and Tomporowski, 2010; Sibley and Etnier, 2003), it is hypothesized that acute exercise will have a significant small beneficial effect on cognitive task performance after exercise, but will negatively affect cognitive performance during exercise. We expect the effects of acute exercise on cognitive performance to be moderated by exercise intensity, timing of the test administration, cognitive task type, and fitness levels.

2. Results

2.1. *Description of studies*

A total of 79 studies and 1034 effect sizes were included in the meta-analytic review. This represented data from 2072 subjects. The average age of the samples was reported in 61 studies and was 28.51 (SD=17.21) with most effects coming from studies testing young adults (20–30 years, n=42 studies) and fewer testing the effects on children (5–20 years, n=9 studies), adults (30–60 years, n=4 studies), and older adults (>60 years, n=6 studies). Effects were calculated from samples consisting only of men (n=492 effects), only of women (n=67 effects), of both men and women (n=415 effects), or when gender was not reported (n=60 effects). Effects were calculated from within-subject comparisons (n=755 effects) and from between subject comparisons (n=279 effects). Most effects came from studies in which a theoretical framework was not identified (n=23 studies), followed by studies specifically testing the inverted-U hypothesis (n=17 studies), attention allocation hypotheses (n=11 studies), and the effects of arousal on performance (n=9 studies).

The overall effect size for the sample was 0.097, SE=0.012, Q(1033)=3047.37, I^2=66, p<.001. Given the moderate to large I^2 value, an examination of the influence of moderating variables on the effects was warranted. Detailed results for all moderators are displayed in Table 2 and findings are described.

2.2. *Paradigm*

The paradigm that was used did not significantly influence the size of the effects. Positive effects that were significantly different from zero were observed when measures were taken during exercise, immediately following the exercise, or after a delay following the exercise.

2.3. *Primary moderators during exercise*

Exercise intensity did not significantly moderate the effects when the cognitive task was administered during the exercise session.

The time of cognitive test administration during exercise significantly influenced the effects such that effects in the first 10 min were negligible, effects after 11–20 min of exercise were negative, and effects after 20 min of exercise were positive.

The general cognitive task type significantly moderated effect size such that the effects for tasks categorized as measures of executive function were significantly larger than any other category of cognitive tasks (for which none of the effects were significantly different from zero).

Fitness level also significantly moderated the effects. Positive effects were evident for highly fit participants, negligible effects were observed for moderately fit participants, and negative effects were found for low fit participants.

2.4. *Primary moderators immediately following exercise*

Exercise intensity had a significant influence such that positive effects that were significantly different than zero were only observed when the exercise was very light, light, or moderate intensity. When the exercise was hard, very hard, or maximal, the effect size was not significantly different from zero.

The general cognitive task type significantly moderated effect size. Effects for tasks categorized as measures of attention, crystallized intelligence, and executive function were not significantly different from one another, but were all significantly larger than the other categories of cognitive tasks (information processing, reaction time, and memory). Of these categories with smaller effect sizes, the only one that was significantly different from zero was information processing. Measures of reaction time and memory were found to be not significantly different from zero.

Fitness level also significantly moderated the effects such that positive significant effects were evident for low fit and high fit participants, but the effect size for moderately fit participants was not significantly different from zero.

2.5. Primary moderators after a delay following exercise

Exercise intensity had a significant influence such that very light exercise resulted in a significant negative effect on cognitive performance, but all other intensity levels resulted in positive effects that were significantly different from zero.

The general cognitive task types significantly moderated effect size such that the effects for tasks categorized as measures of crystallized intelligence and executive function were the largest and were not significantly different from one another. Effects derived from studies assessing information processing, reaction time, and memory were not significantly different from zero.

Fitness level did not significantly moderate the effects when the cognitive tests were performed after delay.

2.6. Primary moderators combining immediately following and after a delay following exercise

When studies that tested cognition following exercise were combined, the timing of the test administration following the exercise did significantly influence the effect sizes observed with tests completed within 0–10 min of exercise completion resulting in significant negative effects, the largest positive effects observed following 11–20 min of delay, and smaller positive effects evident following 20 min of delay.

When assessed following exercise, the duration of the exercise session significantly affected the results with short exercise sessions having a negligible effect on cognitive performance and exercise sessions longer than 11 min resulting in positive significant effects.

2.7. Secondary moderators

2.7.1. Design of the study

There was no difference in effect size as a function of experimental design or sampling method. There was a significant difference in effect size as a function of study quality with the largest effects observed for RCTs and for observational studies comparing cognitive performance prior to and after exercise without randomly assigning to exercise conditions. Controlled observational studies resulted in negative effects that were significantly different from zero.

2.7.2. Sample characteristics

Gender was a significant moderator of the effects such that effects were significantly different from zero only when samples of men and women were tested and effects were not significantly different from zero when samples consisted only of men or only of women. There was no significant difference in effect sizes as a function of the health of the sample. There was a significant difference in effect size relative to the age of the sample with larger positive effects observed for high school, adult, and older adult samples and smaller (but still significantly different from zero) effects observed for elementary and young adult samples.

2.7.3. Acute exercise session

The time of day when the testing occurred had a significant effect on the results such that significantly larger effects were observed for exercise performed during the morning and effects were not significantly different from zero when exercise was performed either in the afternoon or in the evening. When it was reported that exercise was performed at various times of day, the effect size was negative and significantly different from zero.

2.7.4. Specific cognitive tasks

Of the information-processing tasks that were used, effects were only significantly different from zero for visual search and Stroop word and color tasks. The draw-a-line task resulted in negative effects that were significantly different from zero. For reaction time tasks, positive effects that were significantly different from zero were observed for studies using choice reaction time measures, but simple reaction time resulted in significant negative effects. For executive function tasks, significant positive effects were evident for verbal fluency, incompatible reaction time, decision making, and Stroop interference tasks. Significant negative effects were evident for digit span (backward). Significant positive effects were observed for addition and subtraction as a measure of crystallized intelligence and for concentration as a measure of attention. Alternate uses and random number generation tasks resulted in effects that were not significantly different from zero. For memory tasks, positive effects were observed for visual short-term memory and free recall, negative effects for sequential memory and the auditory verbal learning test, and non-significant effects for verbal working memory, digit span (forward), and figural learning.

3. Discussion

When summarized meta-analytically, results from 79 studies indicate that a single bout of exercise has a small positive effect ($d=0.097$) on cognitive performance that is significantly different from zero. This is consistent with conclusions drawn by narrative reviewers (Brisswalter, et al., 2002; McMorris and Graydon, 2000; Tomporowski, 2003a,b) and with the small positive effect reported by Etnier et al. (1997). The first moderator examined in this review was the acute exercise paradigm (cognitive task administered during

Table 2 – Effect size table.

	Q(df)	n ES	Cohen's d	SE	I^2
Overall	Q(1033) = 3047.37, p < .001	1034	0.097*(0.066, 0.129)	0.012	66
	Q(df)	n ES	Cohen's d (95%CI)	SE	
Paradigm	Q(2) = 0.050, p > .05				
During		398	0.101*(0.041, 0.160)	0.030	
Immediately following		397	0.108*(0.069, 0.147)	0.020	
After a delay		218	0.103*(0.035, 0.170)	0.034	
Primary moderators by paradigm — during exercise					
Exercise intensity	Q(5) = 5.303, p > .05				
Very light		53	−0.015(-0.128, 0.098)	0.058	
Light		231	0.092*(0.014, 0.171)	0.040	
Moderate		49	0.193*(0.031, 0.355)	0.083	
Hard		38	0.130 (−0.104, 0.364)	0.119	
Very hard		4	—	–	
Maximal		23	0.138 (−0.133, 0.408)	0.138	
Time of cognitive test administration	Q(2) = 17.993,p < .001				
1–10 min of exercise		111	0.060 (−0.026, 0.147)	0.044	
11–20 min of exercise		144	−0.182*(−0.292, −0.073)	0.056	
>20 min of exercise		21	0.261*(0.043, 0.478)	0.111	
General cognitive task type	Q(5) = 18.783, p < .01				
Information processing		78	0.043 (−0.078, 0.163)	0.062	
Reaction time		218	0.080 (−0.009, 0.170)	0.046	
Attention		2	—	–	
Crystallized intelligence		24	0.110 (−0.119, 0.339)	0.117	
Executive function		44	0.260*(0.119, 0.401)	0.072	
Memory		32	0.013 (−0.077, 0.104)	0.046	
Fitness level	Q(2) = 21.782, p < .001				
Low		21	−0.416*(−0.667, −0.166)	0.128	
Moderate		224	0.016 (−0.059, 0.090)	0.038	
High		82	0.232*(0.103, 0.360)	0.066	
Primary moderators by paradigm — immediately following exercise					
Exercise intensity	Q(5) = 16.765, p < .01				
Very light		89	0.152*(0.039, 0.265)	0.058	
Light		50	0.169*(0.085, 0.254)	0.043	
Moderate		145	0.120*(0.067, 0.173)	0.027	
Hard		64	0.003 (0.073, 0.078)	0.039	
Very hard		6	−0.158 (−0.385, 0.070)	0.116	
Maximal		20	−0.038 (−0.253, 0.177)	0.110	
General cognitive task type	Q(5) = 17.689, p < .01				
Information processing		79	0.091*(0.027, 0.155)	0.033	
Reaction time		97	0.061 (−0.037, 0.158)	0.050	
Attention		7	0.416*(0.173, 0.660)	0.124	
Crystallized intelligence		35	0.271*(0.106, 0.436)	0.084	
Executive function		70	0.189*(0.107, 0.272)	0.042	
Memory		109	0.047 (−0.023, 0.117)	0.036	
Fitness level	Q(2) = 11.880,p < .01				
Low		16	0.169*(0.057, 0.280)	0.057	
Moderate		52	0.029 (−0.055, 0.113)	0.043	
High		67	0.220*(0.150, 0.290)	0.036	
Primary moderators by paradigm — after a delay following exercise					
Exercise intensity	Q(5) = 43.908, p < .001				
Very light		88	−0.113*(−0.198, −0.027)	0.044	
Light		51	0.245*(0.110, 0.379)	0.069	
Moderate		43	0.202*(0.107, 0.298)	0.049	
Hard		15	0.268*(0.032, 0.505)	0.121	
Very hard		20	0.465*(0.105, 0.825)	0.184	
Maximal		1	– –	–	
General cognitive task type	Q(4) = 16.191, p < .01				
Information processing		22	0.113 (−0.167, 0.393)	0.143	
Reaction time		14	0.222 (−0.162, 0.606)	0.196	
Crystallized intelligence		57	0.275*(0.158, 0.393)	0.060	

Table 2 (*continued*)

	Q(df)	n ES	Cohen's d (95%CI)	SE
Executive function		43	0.171*(0.031, 0.312)	0.071
Memory		82	−0.027 (−0.125, 0.071)	0.050
Fitness level	Q(2) = 1.28, p > .05			
Low		23	0.308 (−0.017, 0.633)	0.166
Moderate		74	0.202*(0.096, 0.309)	0.054
High		19	0.331*(0.110, 0.553)	0.113
Primary moderators by paradigm — combining immediately following and after a delay following exercise				
Cognitive administration after exercise	Q(2) = 69.103, p < .001			
0–10 min of exercise performed		202	−0.060*(−0.108, −0.011)	0.025
11–20 min of exercise performed		141	0.262*(0.196, 0.327)	0.033
>20 min of exercise performed		220	0.171*(0.110, 0.232)	0.031
Cognitive administration after exercise	Q(1) = 14.451, p < .001			
1–15 min after exercise completed		511	0.139*(0.102, 0.176)	0.019
>15 min after exercise completed		104	−0.054 (−0.147, 0.038)	0.047
Secondary moderators				
Design of the study				
Experimental design	Q(1) = 1.896, p > .05			
Within		755	0.108*(0.072, 0.144)	0.018
Between		279	0.058 (−0.003, 0.119)	0.031
Sampling method	Q(1) = 3.395, p > .05			
Volunteers from community		825	0.083*(0.048, 0.117)	0.018
Intact group		203	0.160*(0.085, 0.235)	0.038
Study quality	Q(4) = 42.537, p < .001			
Randomized controlled trials		105	0.190*(0.109, 0.272)	0.042
Quasi-experimental studies		104	−0.024 (−0.121, 0.072)	0.049
Controlled observational studies		27	−0.144*(−0.272, −0.016)	0.065
Observational study with randomization		244	−0.024 (−0.100, 0.053)	0.039
Observational study without randomization		554	0.156*(0.116, 0.196)	0.020
Sample characteristics				
Gender of sample	Q(2) = 29.241, p < .001			
Only men		492	0.027 (−0.025, 0.078)	0.026
Only women		67	0.036 (−0.091, 0.163)	0.065
Both men and women		415	0.204*(0.161, 0.246)	0.022
Health of sample	Q(1) = 0.250, p > .05			
Healthy		839	0.100*(0.064, 0.137)	0.019
Impaired		137	0.118*(0.060, 0.175)	0.029
Age	Q(4) = 10.036, p = .040			
Elementary (6–13)		102	0.051 (−.020, .121)	.036
High school (14–17)		73	0.165 (.073, .256)*	.047
Young adult (18–30)		619	0.072 (.028, .115)*	.022
Adult (31–60)		85	0.181 (.080, .281)*	.051
Older adult (60+)		118	0.181 (.073, .290)*	.055
Acute exercise session				
Time of day	Q(3) = 50.750, p < .001			
Morning		18	0.436*(0.310, 0.562)	0.064
Mid-day		–	–	–
Afternoon		20	0.164 (−0.70, 0.398)	0.119
Evening/night		12	−0.224 (−0.478, 0.030)	0.130
Mixed		100	−0.124*(−0.230, −0.028)	0.054
Type of exercise activity	Q(4) = 52.218, p < .001			
Aerobic		936	0.096*(0.064, 0.128)	0.016
Anaerobic		26	−0.744*(−1.107, −0.382)	0.185
Muscular resistance		9	−0.325*(−0.634, −0.016)	0.158
Combination		45	0.371*(0.262, 0.480)	0.056
Accelerometer		6	0.010 (−0.292, 0.311)	0.154
Specific cognitive tasks				
Information processing	Q(7) = 37.440, p < .001			
Finger tapping		5	0.344 (−0.573, 1.261)	0.468
Visual search task		34	0.212*(0.104, 0.320)	0.055
Stroop word or color		40	0.171*(0.63, 0.279)	0.055
Digit symbol substitution		22	0.171 (−0.015, 0.358)	0.095

(continued on next page)

Table 2 (*continued*)

	Q(df)	n ES	Cohen's d (95%CI)	SE
Anticipation/coincident timing task		19	0.009 (−0.258, 0.277)	0.136
Rotor task		15	−0.002 (−0.277, 0.273)	0.140
Tracking task		34	−0.014 (−0.120, 0.092)	0.054
Draw a line task		12	−0.258*(−0.391, −0.124)	0.068
Visual field		–	—	–
Reaction time	Q(3) = 26.610, p < .001			
Simple pre-motor time		3	—	–
Choice pre-motor time		12	0.262 (−0.033, 0.557)	0.151
Choice reaction time		186	0.216*(0.134, 0.299)	0.042
Simple reaction time		128	−0.145*(−0.260, −0.031)	0.058
Attention	Q(1) = 3.789, p > .05			
PASAT		2	—	–
Concentration		7	0.416*(0.173, 0.660)	0.124
Crystallized intelligence	Q(5) = 9.728, p > .05			
Addition and subtraction (Math)		104	0.228*(0.102, 0.354)	0.064
WAIS		6	−0.008 (−0.345, 0.328)	0.172
MMSE		2	—	–
Eysenck's IQ: verbal		3	—	–
Eysenck's IQ: numerical ability		3	—	–
Eysenck's IQ: visuospatial		3	—	–
Executive function	Q(8) = 48.798, p < .001			
Erickson flankers task		4	—	–
Verbal fluency		38	0.314*(0.195, 0.433)	0.061
Incompatible reaction time		9	0.292*(0.136, 0.449)	0.080
Decision making		44	0.300*(0.146, 0.454)	0.079
Stroop interference		14	0.249*(0.106, 0.391)	0.073
Alternate uses		26	0.112 (−0.038, 0.263)	0.077
Trail making test		2	—	–
Random number generation		12	−0.129 (−0.311, 0.054)	0.093
Digit span (backward)		17	−0.307*(−0.553, −0.061)	0.125
Memory	Q(6) = 64.282, p < .001			
Free recall		18	0.485*(0.301, 0.669)	0.094
Visual short-term memory		8	0.234*(0.004, 0.464)	0.117
Verbal working memory		30	0.072 (−0.136, 0.279)	0.106
Digit span (forward)		77	0.059 (−0.017, 0.134)	0.039
Figural learning test		25	0.032 (−0.058, 0.123)	0.046
Sequential memory		18	−0.169*(−0.307, −0.030)	0.071
AVLT		52	−0.250*(−0.349, −0.151)	0.050

Note: PASAT = Paced Auditory Serial Addition Test, WAIS = Wechsler Adult Intelligence Scale, MMSE = Mini-Mental State Exam, IQ = Intelligence Quotient, AVLT = Auditory Verbal Learning Test.

exercise, immediately following exercise, or after a delay following exercise). Results indicate that small positive effects on cognitive performance are evident regardless of when the cognitive task is performed.

The small positive effect observed for cognitive performance during exercise is in contrast to results from Lambourne and Tomporowski (2010) who reported a small negative effect during exercise. The reason for the difference is likely related to the inclusion criteria used for the two meta-analyses. In particular, Lambourne and Tomporowski limited their review to studies (n = 40) that tested the effects in samples of healthy young adults and used within-subjects repeated measures designs. In contrast, this meta-analysis included studies testing the effects with participants of all ages and using any design (n = 79). Thus, the inclusion of studies testing the effects with children and older adults may have contributed to the larger effects. This is supported by our finding that effects for high school aged samples (d = 0.165) and for older adult samples (d = 0.181) were larger than the overall average effect size (d = 0.097). Alternatively, this may simply reflect the inclusion of approximately twice as many studies which may result in a more reliable result. For cognitive tasks performed following exercise, results from this meta-analysis are consistent with the findings of Lambourne and Tomporowski (2010) in showing that exercise has a beneficial effect on cognitive tasks performed following exercise. Moderators were then analyzed within each subgroup of studies relative to the paradigm that was used. In sum, results indicated that regardless of whether the cognitive assessments were taken during exercise, immediately after exercise, or at some time following the exercise, a small beneficial effect was observed.

Within each acute exercise paradigm, exercise intensity was examined first and the results provide indirect evidence

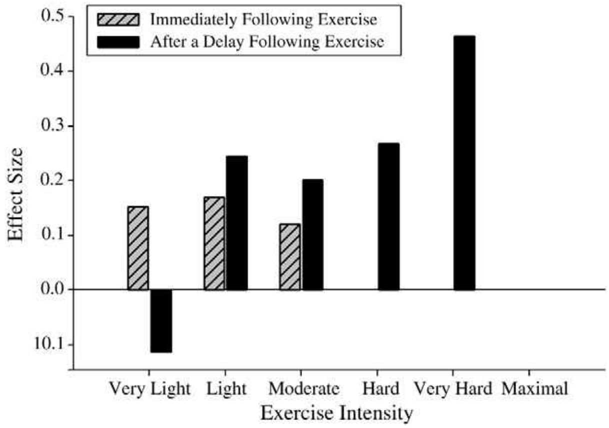

Fig. 1 – Effect size as a function of paradigm and exercise intensity.

as to potential mechanisms of the effects. Findings indicate that exercise intensity does not have a significant effect on cognitive performance assessed during exercise. This clearly argues against the inverted-U hypothesis and against drive theories which predict that exercise intensity impacts cognitive performance. However, when the cognitive performance takes place immediately after exercise, the size of the effect following exercise is impacted in an interactive fashion by the amount of time that passes between exercise and cognitive testing and the intensity of the exercise (see Fig. 1). Specifically, it appears that when performed immediately after exercise, lighter intensity exercise (very light, light, moderate) is more beneficial, but when performed following a delay of more than 1 min, very light intensity exercise no longer has positive effects, and more intense exercise (very hard) results in the biggest effects. This suggests that the mechanisms underlying cognitive benefits are impacted by exercise intensity and that the effects subside fairly quickly following the cessation of the exercise. These findings may suggest that physiological responses to the exercise (e.g., heart rate, brain-derived neurotrophic factor, endorphins, serotonin, dopamine) are themselves predictive of the impact on cognitive performance. In other words, perhaps lower intensity exercise results in the appropriate level of the physiological mechanism immediately post exercise, but higher intensity exercise is necessary for effects to be maximized if there is a delay between the exercise session and the cognitive task performance. This conclusion is further corroborated by the finding that cognitive tests administered 11–20 min after exercise generally result in the biggest effects and that these effects subside following a longer (>20 min) delay.

The effects with regard to the duration of exercise prior to the cognitive test administration are also interesting. When the cognitive task was performed during exercise, a short duration of exercise did not have any effect on cognitive performance. Exercise for only 11–20 min resulted in a negative effect on cognitive performance. Exercise for longer than 20 min resulted in positive effects. These findings are consistent with the conclusions drawn by Brisswalter et al. (2002) who reported that 20 min of exercise was necessary for cognitive benefits. The findings are also generally consistent with those reported by Lambourne and Tomporowski (2010) who observed negative effects when cognitive performance was assessed between 0 and 20 min into the exercise session and positive effects when assessed more than 20 min into the exercise session. This appears, then, to suggest that cognitive activities performed during exercise will benefit if performed after the participant has been exercising for a relatively longer time. Again, this may suggest that physiological mechanisms are relevant and that these mechanisms require some time to reach peak levels necessary to benefit cognition. When examined in studies that had a delay following the exercise, the duration of the exercise session impacted the results such that shorter exercise bouts negatively affected cognitive performance, but longer exercise bouts had positive effects. Thus, whether assessed during exercise or post-exercise, it appears that at least 20 min of exercise is necessary to see effects. That being said, one should recognize that in protocols lasting longer than 20 min, factors of fatigue and dehydration may become increasingly relevant and future research is necessary to explore these effects (Cian et al., 2000, 2001; Tomporowski, 2003b)

With regard to general cognitive task type, positive effects were reported for measures of executive function for all three paradigms. Considered in isolation, this finding is not consistent with the transient hypofrontality hypothesis (Dietrich, 2006; Dietrich and Sparling, 2004) which predicts that measures of executive function would be hampered by exercise that is sufficiently strenuous to require frontal resources. However, to fully consider these results relative to the transient hypofrontality hypothesis requires that the extent to which the exercise is “strenuous” be assessed. Thus, implications relative to this hypothesis will be discussed further when considering the moderators of fitness and exercise intensity. Another important finding for the general cognitive task types is that measures of reaction time yielded non-significant effects. The use of reaction time measures has been very popular in the literature on acute exercise and cognitive performance, especially in studies designed to test the inverted-U hypothesis. Further, past reviews have generally concluded that reaction time measures are sensitive to the effects of acute exercise (Tomporowski, 2003b). Given that the average effect for reaction time measures was not significantly different from zero, this may reflect that there is an influence of exercise intensity on reaction time such that when effects are averaged across intensity levels, the average is null. Alternatively, it may indicate that this measure is not particularly reliable or sensitive as a measure of cognitive performance relative to acute exercise. Similar to reaction time, measures of memory never yielded reliable effects, indicating that this construct might not be particularly sensitive to the effects of acute exercise. However, this conclusion must also be qualified because it is possible that exercise has different effects on different types of memory. Tomporowski concluded that acute exercise does not benefit short-term and working memory, but does benefit long-term memory. This particular conclusion is not consistent with our findings (i.e., that one of the largest memory effects was evident for short-term memory), but is consistent with our observation that all aspects of memory are not positively influenced by acute exercise. That being said, there are individual empirical studies which have clearly demonstrated a positive effect of acute exercise on memory (Ferris et al., 2007; Winter et al., 2007), so future research is necessary to better understand the parameters required to observe positive effects. Lastly, for the after-exercise paradigms, crystallized intelligence measures yielded relatively large effects. Given that crystallized intelligence is not expected to be modifiable in the short-term, this may suggest that the exercise bout is helping with retrieval of stored information. In conjunction with the intriguing memory findings, this is an important direction for future research.

In contrast to the previous conclusion with regard to the cognitive task type findings arguing against the transient hypofrontality hypothesis, the findings with regard to the fitness level of the participants are consistent with the transient hypofrontality hypothesis. When cognitive performance is assessed during exercise, positive effects are evident for participants who are physically fit, but negative effects are evident when participants have low levels of fitness. Based upon the hypofrontality hypothesis, the performance of exercise and cognitive processing require similar neural structures and metabolism. Given the limited and constant metabolic capacity of the brain, neural resources used for conducting exercise compete with the same resources necessary to perform cognitive processing. Our results indicate that a negative effect was only found in participants with lower fitness, implying that participants with lower fitness need more resources when conducting exercise, and therefore have fewer resources available for cognitive performance. In contrast, participants with high fitness need fewer neural resources for the exercise which means there are more neural resources available for cognitive performance. When cognitive performance was assessed following exercise, positive effects were generally observed for all fitness levels. Overall, these findings are generally consistent with Tomporowski and Ellis (1986) whose narrative review led them to conclude that aerobic exercise was beneficial to cognitive performance for physically fit individuals who were tested either during or following exercise.

When the secondary moderators were examined for the entire group of effects, results were observed that may be relevant for directing future research. Of particular importance is the fact that studies using an RCT design yielded effects that were slightly larger than those observed overall. This is important because it suggests that in tightly controlled studies, positive effects remain apparent thus strengthening the support for a causal relationship between acute exercise and cognitive performance. Additionally, although most of the studies did not describe the time of day during which testing occurred, for those that provided this information the effects were largest when testing occurred in the morning as compared to afternoon or evening/night. This may have important implications for researchers interested in improving cognitive performance in the work place or in school-aged persons. This may also provide support for particular physiological mechanisms that are impacted by diurnal rhythms such that larger effects are possible in the morning than in the evening. The findings from the type of exercise activity were somewhat surprising because they indicate that anaerobic forms of exercise and muscular resistance exercise result in negative effects. However, the small number of effects in these categories ($n=26$ and $n=9$, respectively) means that much more research is needed before a final judgment can be made. Importantly, those studies which combined aerobic and resistance exercise yielded the largest effects and these were significantly higher than was observed for aerobic exercise in isolation. This is consistent with findings in the chronic physical activity literature (Colcombe and Kramer, 2003) and may indicate that stimulation of multiple physiological systems yield the biggest gains for cognitive performance. Lastly, effects were examined relative to the particular cognitive task used within each cognitive task category. Within each broad category of cognitive tasks, results indicated that the largest [positive] effects were observed for measures of visual search, Stroop color or word, choice reaction time, [concentration, addition and subtraction,] verbal fluency, incompatible reaction time, Stroop interference, [free recall,] and visual short-term memory. Knowing that these tests yield reliable positive effects can provide important information for researchers interested in furthering our understanding of how acute exercise can impact cognitive performance.

Before drawing conclusions from this review, it is important to emphasize that in any meta-analysis, the interpretation of the moderators is limited by third-order causation. That is, the effects at the level of any moderator can be influenced by another moderator that is not being considered simultaneously. This is a limitation of every meta-analysis and one that cannot be overcome unless sufficient effect sizes are available to examine more than one moderator simultaneously (i.e., in a two-way design). In this meta-analysis, we were able to look at two moderators simultaneously for the primary moderators by testing their effects within subsets of studies created by the particular paradigm used. But, to test additional moderators simultaneously becomes impossible because of the resultant decrease in the number of effect sizes within each possible "cell". Thus, conclusions with respect to the influence of moderators on the results must be interpreted cautiously and future studies must test relevant moderators empirically to adequately assess their influence on the relationship. As an example, consider again our finding that exercise intensity does not influence cognitive performance during exercise. Given that individual studies have found dose–response relationships when testing effects of exercise intensity on cognitive performance during exercise, this meta-analysis reinforces the fact that this is a very complex issue. In other words, it is possible that intensity does influence cognitive performance in certain situations — i.e., with samples of particular fitness levels, performing particular cognitive tasks, exercising for a particular duration of time. These complex effects cannot be effectively explored using meta-analytic techniques and, instead, must be tested empirically and systematically whereby various intensity levels are tested within a given study.

Overall, the results of this meta-analytic review indicate that exercise benefits performance on cognitive tasks performed during or following the exercise bout. The size of the benefit is dependent upon a number of factors, but results indicate that benefits are larger for more fit individuals who perform the physical activity for 20 min or longer. The appropriate intensity depends upon the time of measurement — any intensity benefits cognitive performance during exercise, but lower intensities provide more benefit when the tests are performed immediately after exercise and higher intensities have more durable effects that can be observed even following a delay. Results from the moderator analyses are logical relative to proposed physiological mechanisms. These physiological mechanisms might require a minimum duration of exercise to reach levels high enough to benefit cognition, may benefit from training effects associated with higher fitness levels, and are likely to be transient in nature and hence impacted both by exercise intensity and by the timing of the cognitive assessment following exercise cessation. Future studies should continue to focus on the mechanisms that might explain these results. Understanding mechanisms will allow us to move towards being able to prescribe a particular exercise dose to positively influence cognitive performance.

4. Experimental procedure

4.1. Data collection

Several steps were taken to obtain all possible data relevant to the effects of acute exercise on cognitive performance. First, studies identified from previous reviews (Brisswalter, et al., 2002; Etnier, et al., 1997; McMorris and Graydon, 2000; Tomporowski, 2003b; Tomporowski and Ellis, 1986) were considered for inclusion. Second, computerized searches of the electronic data bases of Sports Discus, Psych Info, Pub Med, ERIC, and High Wire were conducted. Searches were conducted using the logical operator "*and*" between one term from the exercise-related terms "exercise", "physical activity", "physical activity intensity", "exercise intensity", "heart rate", "arousal", "strength", and "physical exercise" and one term from the cognitive-related terms "intelligence", "expertise", "recall", executive function", "mental", "processing", "reaction time", "memory", "perception", "cognitive performance", and "cognition". A final search of the electronic data bases was conducted in February 2010. Third, reference lists from all obtained articles were searched to identify other manuscripts that might be relevant for inclusion. Fourth, we used contact information from all published articles (and updated contact information when available) to solicit unpublished data from first authors whose work was included in this meta-analysis.

4.2. Inclusion criteria

Studies were included in the analysis if they examined the effects of acute exercise on cognitive performance. For this study, acute was defined as "performed on a single day," and exercise was defined based upon the American College of Sports Medicine (American College of Sports Medicine, 2010, p. 2) definition as "a type of physical activity consisting of planned, structured, and repetitive bodily movement done to improve or maintain one or more components of physical fitness." Cognitive performance was defined based upon cognitive domains recognized in current cognitive psychology and neuropsychology texts (Balota and Marsh, 2004; Lamberts and Goldstone, 2005; Lezak et al., 2004; Reisberg, 2006). These domains included information processing, speeded performance, attention, knowledge and expertise, executive functioning, and memory.

4.3. Coding

Coding instructions were developed and pilot tested (coding instructions available from first author). Coding of studies was performed by three of the study authors (JIG, JDL, YKC). To insure that coding was performed consistently across studies, pairs of coders initially coded 10 studies independently and then compared their data. During this first stage of coding, the average inter-rater reliability was high (96%) for all pairs of coders. In instances where the coders disagreed as to the appropriate code, a third coder (JLE) joined the discussion and a consensus was reached. From this point on, all effects were coded by a single person and were reviewed by JLE.

4.4. Paradigm

Paradigm describes when cognitive performance was assessed relative to performance of the exercise session. This variable was coded as: during exercise, immediately following exercise (≤1 min), or after a longer delay (>1 min following exercise). Four primary moderators were then examined for each paradigm separately.

4.5. Primary moderators

4.5.1. Exercise intensity

The intensity of the exercise performed by the treatment group was coded when intensity was provided as percentage of maximal heart rate (HRmax), VO_2, watts, or power. When average heart rate and average age were provided, HRmax was estimated. The intensity was then coded based upon the American College of Sports Medicine (2010) guidelines as very light (<50% HRmax), light (50–63% HRmax), moderate (64–76% HRmax), hard (77–93% HRmax), very hard (>93% HRmax), or maximal (100% HRmax).

4.5.2. Time of cognitive test administration and duration

Paradigm describes broadly when the cognitive test is administered relative to the exercise and this variable provides more specific information relative to the timing of the cognitive test. For cognitive tests performed during exercise (paradigm), this variable was the number of minutes of exercise completed prior to the test. This was then categorized as 0–10 min, 11–20 min, or >20 min. This variable could also be considered a measure of the duration of the exercise session.

For cognitive tests performed after exercise, studies testing the effects immediately post exercise (paradigm) and after a delay (paradigm) were combined, and this variable was the number of minutes following exercise after which the test was administered (coded as 0–15 min or >15 min). Additionally, for this combined set of studies, effects were tested relative to the length of the exercise session which, again, would be considered a measure of the duration of the exercise session. This variable was coded as 0–10 min, 11–20 min, or >20 min.

4.5.3. General cognitive task type

The cognitive task was identified based upon the particular test that was administered and was coded into a general cognitive task category using test categories identified by Lezak et al. (2004) (see Table 1).

4.5.4. *Fitness of participants*

When provided, the actual fitness level for the sample was recorded. This was then converted to a categorical descriptor based upon ACSM guidelines and was recorded as sedentary or low, moderate, or high. When the actual fitness level was not provided, the fitness level of the sample was based upon the description of the sample provided by the author(s) and was coded as sedentary or low, moderate, or high.

4.6. *Secondary moderators*

Additional moderators were examined to explore their potential influence on the effect sizes observed. Because these moderators would not be expected to differentially influence the findings as a function of the exercise paradigm and so that they would be maximally powered, they were tested for all studies simultaneously.

4.6.1. *Design of the study*

For descriptive purposes, studies were coded to identify common hypotheses that the study might have been designed to test (inverted U, central fatigue, cardiovascular fitness hypothesis, attention allocation, cognitive energetic model, executive control, arousal, transient hypofrontality hypothesis, duration effects, sleep deprivation, and Humphrey and Revelle's model of problem solving). The experimental design was coded as a within-subjects or a between-subjects design. Study quality was determined based upon the study design hierarchy proposed by Khan et al. (2001) and studies were identified as being randomized controlled trials (RCTs), quasi-experimental studies, controlled observational studies, or observational studies that either randomly assigned to the order of exercise conditions or did not randomly assign to the order of exercise conditions.

4.6.2. *Sample characteristics*

The sample was identified as being made up of only men, only women, or a combination of men and women. For studies using a sample of both men and women, the percent of female participants was recorded. The health of the sample was recorded as healthy or impaired (either cognitively or physically). Age was determined based upon either the age range reported or the average age of the sample and was categorized as elementary (6–13 years), high school (14–17 years), young adult (18–30 years), adult (31–60 years), and older adults (over 60 years).

4.6.3. *Acute exercise session*

The time of day when the exercise session was administered was coded as morning (before noon), afternoon (noon to 5 pm), or evening (after 5 pm and before midnight). The duration of the exercise bout was recorded in minutes. The type of exercise activity was coded as aerobic, anaerobic, muscular resistance, a combination of exercise types, or physical activity as assessed using an accelerometer.

4.6.4. *Specific cognitive task type*

In addition to testing the primary moderator of general cognitive task type, specific measures of cognition were also coded. Effects were then tested as a function of the specific cognitive task type within each general cognitive task category.

4.7. *Analyses*

Descriptive information was calculated using SPSS v. 17. Effect sizes were calculated and meta-analyses were conducted using Comprehensive Meta-Analysis v. 2.2.048. When means, standard deviations, and sample sizes were available, Cohen's d was calculated. When this data was not available, Cohen's d was estimated using t or F values and sample size information. Cohen's d was used as the measure of the effect because of evidence that Type I error rates for tests of heterogeneity are well controlled using this metric (Huedo-Medina et al., 2006). The sign of the effect was calculated such that positive effect sizes are indicative of a beneficial effect of acute exercise on cognitive performance. Because sample size impacts the precision of the effect size estimate, each effect size was weighted by the inverse of its variance prior to conducting further analyses. A mixed effects model, which addresses concerns regarding the lack of independence of the data points when multiple effects are calculated from a single study, was used to calculate the overall ES (Lipsey and Wilson, 2000).

The heterogeneity of the effects was calculated using the I^2 statistic. The I^2 statistic expresses the ratio of the observed variance between outcomes to the total observed variance in effect sizes (Huedo-Medina, et al., 2006). I^2 values are interpreted as low (25), moderate (50) and high (75) (Higgins and Thompson, 2002). Primary moderators (exercise intensity, timing of the cognitive assessment, general cognitive task type, and fitness level) were tested statistically using alpha = 0.05. A Bonferroni correction to adjust alpha for the number of statistical tests conducted was used when assessing the impact of secondary moderators of interest (alpha = .05/8 tests = .006) and the particular types of cognitive tests with each cognitive category (alpha = .05/6 categories = .008) to provide direction for future research. Moderators were tested using Q with a mixed effects analysis. All analyses were conducted after excluding effect sizes from studies that did not report on the moderator of interest, and average effect sizes for levels of the moderator for which there were fewer than 5 effect sizes are not presented or discussed (Lambourne and Tomporowski, 2010).

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