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Effects of acute bouts of exercise on cognition

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Abstract

A review was conducted of studies that assessed the effects of acute bouts of physical activity on adults' cognitive performance. Three groups of studies were constituted on the basis of the type of exercise protocol employed. Each group was then evaluated in terms of information-processing theory. It was concluded that submaximal aerobic exercise performed for periods up to 60 min facilitate specific aspects of information processing; however, extended exercise that leads to dehydration compromises both information processing and memory functions. The selective effects of exercise on cognitive performance are explained in terms of Sanders' [Acta Psychol. 53 (1983) 61] cognitive-energetic model.

Keywords: Exercise; Cognition; Cognitive processing speed; Fatigue

1. Introduction

Proponents of exercise report that brief bouts of exercise help them think more clearly and improve their mood and psychological well-being. There is considerable support for the view that an acute bout of exercise has a positive impact on mood states and affect (Morgan & O'Connor, 1988; Raglin, 1997). A panel of experts conducting a review of research for the National Institute of Mental Health concluded that exercise is positively related to several indices of mental health (Morgan, 1984). Exercise is associated with a reduction in physiological measures of stress and psychological measures such as anxiety and depression. Further, exercise is associated with elevations in mood states and heightened psychological well-being (Berger,

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1996; Shephard, 1996). The view that bouts of physical activity influence cognitive function is less well substantiated by empirical research, however. An early review of the exercise literature found little support for the notion that exercise significantly influences cognition (Tomporowski & Ellis, 1986). A similar conclusion was reached in more recent reviews (Etnier et al., 1997; McMorris & Graydon, 2000).

The present review evaluates the exercise literature in terms of an information-processing model of cognition (Proctor, Reeve, & Weeks, 1990). This model assumes that behavior is the result of information that is extracted from the environment and processed through a series of three non-overlapping stages, each operating independently of the others. The three stages include the stimulus-identification stage, which involves a number of discrete processes through which sensory events are transformed and given meaning; the response-selection stage, which is characterized by processes that determine what response, if any, will be made to an environmental event; and the response-programming stage, which prepares the motor system for movement. Considerable experimental research conducted over the past four decades has isolated and examined the function of a variety of information-processing system components. The information-processing model has been promoted as a useful framework to assess the impact of such factors as pharmacological agents (Callaway, 1983; Sergeant, Oosterlaan, & van der Meere, 1999; White & Rumbold, 1988) and exercise (Arcelin, Brisswalter, & Delignierres, 1997; Tomporowski & Ellis, 1986) on cognition. A theory-based evaluation of exercise studies grouped on the basis of common methodologies was hypothesized to elucidate exercise–cognition relations not detected in previous reviews.

2. Review of the literature

The review is limited to exercise studies that involved the activation of the entire body and produce systemic changes in physiological functions (e.g., cardiorespiration, endocrine function, body temperature change) and that assessed the acute effects of this activation on cognitive performance; that is, measures of cognitive performance were taken while the individual was in the process of exercising or shortly following the termination of exercise. The studies selected for evaluation were separated into three groups, based on each study's primary focus and based on the exercise protocol employed (see Table 1). One group of studies is representative of research conducted to assess the effects of intense levels of exercise on cognitive function; these studies typically use maximal anaerobic exercise protocols. A second group of studies addresses the relation between exercise-induced arousal and cognitive performance. The notion that performance is associated with arousal level has long been part of psychological research. The formulation of the Yerkes–Dodson Law (Yerkes & Dodson, 1908), which hypothesizes an inverted U-shaped function between arousal and performance, figured prominently in early learning theory (Hull, 1943) and has had an impact on modern theories of human performance (Easterbrook, 1959; Oxendine, 1984). The third group of studies focuses on the effects that relatively long, submaximal aerobic exercise exerts on mental processing.

Table 1
Summary of findings of studies performed to assess the acute effects of exercise on cognition

Author(s)	*n*	Time of test	Exercise intervention	Cognitive task	Results
Intense anaerobic exercise					
Bard and Fleury (1978)	16	During	Cycling to exhaustion	Letter detection	No effect
				Spatial location	No effect
				Coincidence timing	No effect
Fleury, Bard, Jobin, and Carriere (1981)	31	During	Treadmill run—3 protocols	Letter detection	No effect
Gutin and DiGennaro (1968a)	72	After	Treadmill run to exhaustion	Mathematics computation	No effect
Hancock and McNaughton (1986)	6	During	Treadmill run at anaerobic threshold	Short-term memory	Facilitation
				Time estimation	Facilitation
				Symbol interpretation	Impairment
Isaacs and Pohlman (1991)	12	During	Cycling progressively to 100% $VO_{2\,max}$	Coincidence timing	Impairment at highest intensity
Wrisberg and Herbert (1976)	24	After	Treadmill run to exhaustion	Coincidence timing	Impairment
Short-duration aerobic and anaerobic exercise					
Allard, Brawley, Deakin, and Elliot (1989)					
Exp. 1	30	During	Cycling at 0%, 30%, 60% $VO_{2\,max}$	Visual search	Faciliation
Exp. 2	8	During	Cycling at 30%, 70% $VO_{2\,max}$	Letter matching	No effect
Arcelin et al. (1997)	22	During	Cycling at 0%, 60% $VO_{2\,max}$	Choice–discrimination	Facilitation
Aks (1998)	18	After	Cycling aerobically, anaerobically	Visual search	Facilitation
Brisswalter, Durand, Delignieres, and Legros (1995)	18	During	Cycling at progressively faster rates	Simple RT	U-shaped facilitation
Chmura, Nazar, and Kaciuba-Ulscilko (1994)	22	During	Cycling at progressively greater load	Choice RT	U-shaped facilitation
Cote, Salmela, and Papthanasopoloulu (1992)	17	During and after	Cycling at progressively higher HR	Choice RT	No effect
Delignieres et al. (1995)	40	During	Cycling at 20%, 40%, 60%, 80% $VO_{2\,max}$	Choice RT	Facilitation for experts; impariment for novices
Gutin and DiGennaro (1968b)	55	After	Step-ups 1, 5 min	Mathematics computations	Facilitation for fit
Levitt and Gutin (1971)	20	During	Treadmill run at progressively higher HR	Choice RT	U-shaped facilitation

Table 1 (*continued*)

Author(s)	*n*	Time of test	Exercise intervention	Cognitive task	Results
McGlynn, Laughlin, and Bender (1977)	14	During	Treadmill run at progressively faster speed	Visual discrimination	Facilitation
McGlynn, Laughlin, and Rowe (1979)	15	During	Treadmill run at progressively faster speed	Visual discrimination	Facilitation at highest speed
McMorris and Keen (1994)	15	During	Cycling at 0%, 70%, 100% MPO	Simple RT	Impairment at highest load
McMorris and Graydon (1996a)	20	During	Cycling at 0%, 70%, 100% MPO	Decision making in soccer	No effect on accuracy; facilitation of speed
McMorris and Graydon (1996b)					
Exp. 1	10	During	Cycling at 0%, 70%, 100% MPO	Decision making in soccer	No effect on accuracy; facilitation of speed
Exp. 2	20	During	Cycling at 0%, 70%, 100% MPO	Decision making in soccer	No effect on accuracy; facilitation of speed
McMorris and Graydon (1997a)	16	During	Cycling at 0%, 70%, 100% MPO	Decision making in soccer	No effect on accuracy; facilitation of speed
McMorris and Graydon (1997b)					
Exp. 1	12	During	Cycling at 0%, 70%, 100% MPO	Visual search in soccer	Facilitation
Exp. 2	12	During	Cycling at 0%, 70%, 100% MPO	Decision making in soccer	Facilitation of accuracy and speed
McMorris et al. (1999)	9	During	Cycling at 0%, anaerobic threshold, 100% MPO	Decision making in soccer	No effect on accuracy; facilitation of speed
Reilly and Smith (1986)	10	During	Cycling at 0, 25, 40, 55	Mental arithmetic	U-shaped facilitation
				Pursuit rotor	U-shaped facilitation
Salmela and Ndoye (1986)	10	During	Cycling at progressively higher HR	Choice RT	U-shaped facilitation
Sjoberg, Ohlsson, and Dornic (1975)	48	During	Cycling at 0%, 25%, 50%, 75% $VO_{2\,max}$	Short-term memory	Facilitation
				Paired-associate memory	No effect
Sjoberg (1980)	48	During	Cycling at 0%, 25%, 50%, 75% $VO_{2\,max}$	Short-term memory	No effect
				Paired-associate memory	No effect
		After		Mathematical computation	Impairment of low fit
Tenenbaum et al. (1993)	118	During	Treadmill run of moderate and high speed	Decision making in handball	Facilitation

Table 1 (*continued*)

Author(s)	*n*	Time of test	Exercise intervention	Cognitive task	Results
Steady-state aerobic exercise					
Adam, Teeken, Ypelaar, Verstappen, and Paas (1997)	20	During	Cycling 40 min at submaximal loads	Perception task	Facilitation
				Decision task	Facilitation of speed
Arcelin, Delignieres, and Brisswalter (1998)	22	During	Cycling 30 min at 60% $VO_{2\,max}$	2-choice RT	
				Stimulus discrimination	No effect
				Response compatibility	No effect
				Foreperiod duration	Facilitation
Cian et al. (2000)	8	Following	Running 2 h at 60% $VO_{2\,max}$ to dehydration	Choice RT	No effect
				Tracking	Impairment
				Perceptual discrimination	Impaired RT
				STM	Impairment
				LTM	No effect
			Following hydration and arm exercise	Choice RT	No effect
				Tracking	Impariment
				Perceptual discrimination	No effect
				STM	No effect
				Free-recall memory	Impairment
Cian, Barraud, Melin, and Raphel (2001)	7	Following	Running 2 h at 65% $VO_{2\,max}$ to dehydration	Choice RT	No effect
				Tracking	No effect
				Perceptual discrimination	Imparied RT
				STM	Impairment
				Free-recall memory	No effect
			Following hydration	Choice RT	No effect
				Tracking	No effect
				Perceptual discrimination	Impaired RT
				STM	Facilitated
				Free-recall memory	No effect
Fleury et al. (1981)	15	After	Cycling 45 min at 66% $VO_{2\,max}$	Coincidence timing	Facilitation

Table 1 (*continued*)

Author(s)	*n*	Time of test	Exercise intervention	Cognitive task	Results
Fleury and Bard (1987)	18	After	Treadmill runs—3 protocols	Coincidence timing	Facilitation
				Stimulus detection	Facilitation
Gondola (1987)	21	After	Aerobic dance 20 min	Alternate uses	Facilitation
				Remote response	Facilitation
				Obvious response	Facilitation
Heckler and Croce (1991)	18	After	Treadmill runs of 20, 40 min at 55% $VO_{2\,max}$	Mathematics computations	Facilitation for fit women
Hogervorst, Riedel, Jeukendrup, and Jolles (1996)	15	After	Cycling 60 min at 75–85% $VO_{2\,max}$	Simple RT	Facilitation
				Choice RT	No effect
				Tapping	No effect
				Stroop	Facilitation
Lichtman and Poser (1983)	10	After	Aerobic run of 45 min	Stroop	Facilitation
Marriott, Reilly, and Miles (1993)	16	After	Treadmill runs of 45, 90 min at 157 betas min^{-1}	Decision making in soccer	Facilitation of accuracy
Paas and Adam (1991)	16	During	Cycling 40 min (two protocols)	Decision task	Facilitation
				Perception task	Impairment and facilitation
Tomporowski, Ellis, and Stephens (1987)					
Exp. 1	24	After	Treadmill run 50 min at 80% $VO_{2\,max}$	Free-recall memory	No effect
Exp. 2	12	After	Treadmill run	Free-recall memory	No effect
Tomporowski, Armstrong, and Kane (submitted for publication)	8	After	Cycling 40 min at 60% $VO_{2\,max}$	Response inhibition	Facilitation
Travlos and Marisi (1995)	20	During	Cycling 50 min with progressive load	Concentration	No effect
				Choice RT	No effect

n—number of participants; RT—reaction time; STM—short-term memory; $VO_{2\,max}$—maximum volume of oxygen uptake; MPO—maximum power output.

The studies evaluated were identified from citations in previous literature reviews and by key-word searches of select data bases (PsycINFO, MEDLINE, and PubMed).

2.1. Intense exercise and cognitive function

Researchers who examine the impact of intense exercise on mental performance typically design protocols that place maximal anaerobic demands on participants. In most cases, these studies are based on the a priori expectation that intense anaerobic exercise will produce a fatigue state in participants, which will lead to declines in their cognitive performance. Typically, exercise protocol bouts are intense and brief, with most lasting only a few minutes. The effects of exercise on cognitive performance are typically assessed immediately following physical activity; however, these effects have also been assessed during maximal exertion.

Researchers who have examined the effects of anaerobic exercise on cognitive processes have consistently failed to detect a clear relation between exhaustive exercise and processes involved in perception, sensory integration, or discrimination. An early study conducted by Bard and Fleury (1978) assessed the effects of cycling to voluntary exhaustion on 16 young adults' visual search task performance. Participants pedaled continuously 6 min at a 150-W power output, 3 min at a 200-W output, and then against resistive loads that increased power output by 25 W every minute. The exercise bout did not influence participants' target detection or spatial location performance. Later, Fleury et al. (1981) evaluated the effects of two different treadmill protocols on young men's visual perception. One protocol required participants to run five 1.5-min bouts at a speed that elicited exertion comparable to 150% of $VO_{2\,max}$ at 5-min intervals; the other protocol required men to run continuously to voluntary exhaustion while the speed and grade of the treadmill was increased. Neither exercise treatment influenced participants' performance during a letter-detection task.

Intense exercise appears to have transient detrimental effects on processes that control response preparation, however. Wrisberg and Herbert (1976) found that fatigue produced by a treadmill run to voluntary exhaustion led to a brief transitory degradation of participants' coincidence-timing performance. Likewise, Isaacs and Pohlman (1991) observed that participants' coincidence-anticipation timing performance degraded, but only minimally, when they cycled an ergometer at 100% of $VO_{2\,max}$. In general, laboratory tests of cognitive function appear to be quite resistant to putative fatigue states produced by intense anaerobic exercise. When exercise-related decrements have been found, they have tended to be small and transitory.

There is evidence that intense exercise may facilitate some aspects of cognitive function. Hancock and McNaughton (1986) evaluated the effects of intense exercise on young men's abilities to evaluate and interpret topographical maps. Six trained orienteers, who had extensive experience in reading maps and plotting directions, interpreted a series of maps while running on a treadmill at near anaerobic threshold. The exercise produced selective effects on participants' performance. Compared to their performance at rest, their ability to make global interpretations of the information presented on the maps decreased; however, their short-term memory and time estimations improved. The investigators concluded that exercise differentially affects low-level and high-level cognitive processes.

An individual's fitness level may play a role in determining the impact that intense exercise has on his or her cognitive function. Gutin and DiGennaro (1968a), for example, observed that while a treadmill run to voluntary exhaustion did not influence young adults' speed or accuracy of calculating simple mathematics problems, individuals classified as high fit performed the task significantly better than did individuals classified as low fit.

Given the number of instances in which declines in worker performance are attributed to physical fatigue, the failure of laboratory-based studies to find clearly measurable decrements in cognitive performance following brief bouts of intense exercise may appear counterintuitive. However, the lack of compelling evidence that links bouts of anaerobic exercise to changes in cognition may be explained in terms of the rapid recovery from physiological fatigue that follows brief bouts of physical activity. Recent studies, which are reviewed later in this paper, provide evidence that long-duration, steady-state exercise that leads to dehydration and depletion of energy storage produce decrements in cognitive functioning. It is also important to remember that human factors researchers have long recognized the difficulties involved in defining the construct of fatigue operationally and measuring the effects of fatigue under laboratory conditions (Gawron, French, & Funke, 2001; Holding, 1983; Soames Job & Dalziel, 2001).

2.2. Exercise-induced arousal and cognitive performance

A number of experiments have been designed based on a priori predictions derived from theories grounded in the Yerkes–Dodson Law. These studies are characterized by the repeated assessment of an individual's cognitive performance as his or her level of physical arousal increases as a direct function of exercise. Typically, exercise protocols include bouts of aerobic and bouts of anaerobic exercise that are relatively brief, with most protocols lasting less than 20 min. Demonstration of an initial improvement in performance followed by a decline in performance as arousal increases from a resting state is taken as support for the Yerkes–Dodson Law.

The results of laboratory studies that attempt to link cognitive performance to specific levels of exercised-produced arousal are ambiguous. There are studies that provide clear evidence for an inverted U-shaped relation between arousal and cognitive performance, studies that provide only partial support for the relation, and still other studies that provide no support for the relation.

Five of the experiments reviewed provide compelling evidence for an inverted U-shaped function. An early study conducted by Levitt and Gutin (1971) assessed men's reaction times and movement times on a choice-response task while walking on a treadmill at speeds that produced heart rates of 115, 145, or 175 beats min^{-1}. Participants' reaction times followed a curvilinear relation; reaction time improved when heart rate increased to 115 beats min^{-1}, returned to basal levels at 145 beats min^{-1}, and dropped below basal levels at 175 beats min^{-1}. Participants' movement time improved linearly as a function of heart rate. Salmela and Ndoye (1986) examined the effects of progressive cycling demands on participants' performance during a 5-choice spatial reaction time task. They reported that cognitive performance followed an inverted U-shaped function, with reaction time being faster when heart rate was at 115 beats min^{-1} than during rest or at 145 beats min^{-1}. They also reported a lengthening of reaction time to peripheral cues at high levels of physical exertion, which was explained in terms of a narrowing of attention brought about by intense levels of exercise. A replication conducted by Cote et al. (1992), however, failed to find that exercise facilitates choice-reaction time or that exercise results in a narrowing of attention.

Brisswalter et al. (1995) examined how simple reaction time performance was influenced by pedaling at seven different rates at an identical power output on a cycle ergometer. An inverted U-shaped function was observed, with the fastest reaction times corresponding to mid-range pedaling rates (50 rev min^{-1}) and the longest reaction times corresponding to the highest pedaling rate (80 rev min^{-1}). A unique study performed by Chmura et al. (1994) determined that participants' reaction times to a discriminative choice-response test were related both to the resistive load experienced while cycling and to measures of plasma adrenaline and noradrenaline concentrations taken during exercise. Participants' reaction times decreased linearly as resistive load increased from 0 to 250 W power output, which corresponded to 76% $\text{VO}_{2\,\text{max}}$, and then increased dramatically when the resistive load was increased to 300 W. Importantly, the relation between reaction time and plasma catecholamine can be described as a U-shaped curve.

The effects of different exercise workloads on 10 young men's perceptual-motor performance and on their cognitive performance was reported by Reilly and Smith (1986). In each of two studies, participants cycled for 6 min against resistance loads that corresponded to 0%, 25%, 40%, 55%, and 85% $\text{VO}_{2\,\text{max}}$. In one study, participants performed a pursuit-rotor task during the latter part of each cycling bout; in the other study, participants performed an arithmetic computation task. The men's performance on both tasks approximated a U-shaped function. Psychomotor performance improved with workloads increasing up to approximately 40% $\text{VO}_{2\,\text{max}}$ and then declined with the higher workload requirements. Cognitive performance was enhanced at workloads ranging between 25% and 70% $\text{VO}_{2\,\text{max}}$ and it was compromised at a workload of 85% $\text{VO}_{2\,\text{max}}$.

In summary, in five studies, participants' speed of responding and the speed of decision making was facilitated by exercise as demands were increased, but a point was reached at which exercise resulted in declines in performance. It is not possible to assess a speed–accuracy relation in the studies conducted by Levitt and Gutin (1971) or Chmura et al. (1994), as participants' error rates were not reported.

The majority of the studies reviewed report that exercise-induced arousal influences cognitive performance, but it does not follow the U-shaped function predicted by theories derived from the Yerkes–Dodson Law. Within these studies, the most robust finding is that participants' response speed is affected by exercise; responses are made more quickly during exercise periods than during non-exercise or during periods of low-intensity exercise. Improved response speed has been shown during simple detection tasks (McMorris & Keen, 1994), visual search tasks (Aks, 1998; Allard et al., 1989), discriminative choice-response tasks (Arcelin et al., 1997; Delignieres, Brisswalter, & Legros, 1994; McGlynn et al., 1977, 1979), and complex problem-solving tasks (McMorris & Graydon, 1996a,b, 1997a,b; McMorris et al., 1999; Tenenbaum et al., 1993).

Early studies conducted by McGlynn et al. (1977, 1979) examined young adults' performance during a visual size-discrimination task while subjects ran on a treadmill at four different speeds and graduated inclines. In both studies, the number of problems completed by runners increased when they exercised. In the first study in 1977, subjects performed more problems within a set time period with no associated reduction in decision-making accuracy. The number of problems completed was directly related to the level of exercise experienced by the subject. Similar results were obtained in the second study in 1979; however, improvements in young women's speed of decision making was detected only at the highest exercise level.

Clear evidence for the effects of exercise on speed of visual search and speed of response has been provided in three studies. Allard et al. (1989) conducted two experiments that assessed the effects of aerobic exercise on visual perception. The first experiment evaluated the impact of cycling at 0%, 30%, and 60% $VO_{2\,max}$ on the speed of young men's visual search. Subjects' search speed was most rapid when exercising at the high exercise workload; further, search times improved for single features as well as conjoined targets, suggesting that exercise influenced both automatic and effortful processing. Importantly, there was no change in error rate with improvement in search speed. The basis for the facilitating effect of exercise on visual perception was examined in the second experiment. Subjects performed a letter-matching task that required them to judge whether pairs of letters were physically the same or different while cycling at either 30% or 70% of their estimated maximal workload. Exercise was found to have no effect on the manner in which subjects encoded information, but rather it facilitated preparation time. Similar results have been obtained recently by Aks (1998). She evaluated participants' performance during a visual feature and conjunction search task after 10 min of cycling at a low level of exertion and then again after a high level of exertion. Participants' visual search speed increased and their frequency of errors decreased following both exercise protocols; performance was most improved following high-level exertion. Likewise, Arcelin et al. (1997) measured subjects' choice-reaction times while participants exercised on a cycle ergometer at 60% of their $VO_{2\,max}$. The cognitive task was administered after 3 min of exercise and again after exercising 8 min. Subjects' reaction times were significantly shorter during exercise than when they were not exercising; further, reaction times were shorter at the end of the exercise period than at the beginning. Taken together, the studies of Aks (1998), Allard et al. (1989), and Arcelin et al. (1997) suggest that exercise does not influence directly the encoding of stimuli. Rather, exercise exerts a selective influence on the manner in which an individual prepares for the onset of a stimulus event.

Participants' response accuracy has been shown to be facilitated by exercise intensity; however, the evidence is not as unambiguous as that found when response speed is measured. An early study conducted by Sjoberg et al. (1975) reported that young men's short-term memory performance was significantly better when cycling at 75% $VO_{2\,max}$ than when cycling at lower exertion levels. A later study by Sjoberg (1980), however, failed to replicate these findings; he reported that exercise had no effect on men's short-term memory nor on paired-associate test performance during exercise nor on the accuracy of mathematical computations immediately following exercise. More recently, the study by Tenenbaum et al. (1993) assessed 118 team handball player's decision-making abilities while subjects walked and ran on a treadmill. The cognitive task simulated game situations experienced while playing team handball. The men were presented a series of visual scenarios that depicted specific handball situations. Nineteen slides were presented for 2 s each; participants indicated verbally their response to the situation. These responses were rated and scored by a panel of experts. Participants' decision making, regardless of level of handball playing experience, was significantly better during high exercise levels than during low exercise.

The results obtained by Tenenbaum et al. (1993) are important in light of a series of recently published reports by McMorris and his colleagues. They employed cognitive tests similar to those used by Tenenbaum et al. (1993), but consistently reported that exercise influences peoples' response speeds but has little or no effect on decision-making processes. A rather detailed overview of these studies is provided, because of their central importance in a recently published review (McMorris & Graydon, 2000).

The methods developed by McMorris and his colleagues to assess the effects of exercise on cognitive performance are similar across each of five published studies. The cognitive tasks were designed to simulate decision making during soccer play. Pictures were taken of displays of specific game play scenarios, created by using models of soccer players placed at various positions on a table tennis table. Pictures were made into slides, which were presented via a projector. Slides were displayed for 2 s and the participant was asked to choose, as quickly as possible, one of four play responses: pass, shoot, dribble, or run. Participants' speed of vocal response and accuracy of their choice were recorded on each trial. The participants in each study were young adult male soccer players. Testing procedures were conducted over two sessions. The initial session involved obtaining a measure of individual subject's maximal power output (MPO) via an incremental test to exhaustion, and providing the participant an opportunity to practice the cognitive task. The second session assessed participants' cognitive performance while sitting on a cycle ergometer, exercising at 70% MPO, and again while exercising at 100% MPO. The total duration of the cycling period was approximately 20 min.

One of the first studies reported by McMorris and Graydon (1996a,b) contrasted 10 experienced and 10 inexperienced soccer players' cognitive performance under test conditions describe above. Participants were shown 10 slides that depicted game situations while at rest, exercising at 70% MPO, and again at 100% MPO. The exercise protocols resulted in significant increases in response speed for both experienced and inexperienced soccer players. The exercise conditions did not influence participants' accuracy of choice responses. The authors conceded, however, that participants' accuracy performance was high and ceiling effects may have obscured the effects of exercise on their decision making.

McMorris and Graydon (1996b) addressed directly the possible experimental confound due to ceiling effects in a subsequent study by manipulating task complexity. In the first of two experiments, 10 soccer players performed the decision-making test used by McMorris and Graydon (1996a) in one session and performed a more complex task during another session. The complex-decision test required participants to make the same 4-choice decision as in the simple condition, but the subjects were asked to make their selection from the perspective of one of the players shown on the slide. As in the previous study, 10 slides were presented at rest, at 70% MPO, and at 100% MPO. Participants' performed the complex task significantly less accurately and more slowly than they performed the simple task. The exercise protocol resulted in a significant decrease in subjects' speed of decision with no effect on accuracy of decision on either simple- or complex-decision tasks. A second experiment was designed to determine whether participants' choice responses and response speed were influenced by the instructions provided to them in the first experiment. Twenty soccer players performed the complex-decision task; 10 were given instructions that emphasized speed of decision and 10 players were given instructions that emphasized accuracy of decision. The exercise protocol resulted in increased speed of decision making with no effect on accuracy of decision, regardless of the instructions provided. These results were interpreted by the authors as evidence for the view that exercise-produced arousal is limited to the facilitation of the speed of information processing; exercise impacts performance during simple reaction time and search tasks, but has little influence on cognitive processes that are involved in complex decision making.

The notion that exercise affects speed detection tasks led McMorris and Graydon (1997a) to examine the impact of cycling exercise on soccer players' speed of visual search. Two experiments were conducted; the first evaluated players' speed of searching familiar soccer and unfamiliar soccer scenarios. Twelve players were instructed to view 30 slides of soccer plays and to determine as quickly as possible the presence or absence of a soccer ball from the slide presented. The exercise protocol's effect was selective; response speed declined only at 100% MPO and speed of search was faster to unfamiliar play scenarios only. The second experiment evaluated the effects of exercise on soccer players' visual search time, choice-response speed, and choice-response accuracy. The cognitive task required participants to search each of 15 slides that showed familiar soccer scenarios and to press a button when they detected a ball (target stimulus) and then to choose one of four play options. Unlike previous studies, the exercise protocols facilitated both speed and accuracy of decision making. The finding that exercise facilitates response accuracy was treated by the authors as an anomaly. A replication by McMorris and Graydon (1997b) and a study conducted by McMorris et al. (1999) led the researchers to conclude that exercise-induced arousal is limited to information-processing speed and has little influence on the types of complex decisions found in sport situations.

These studies represent a considerable effort on the part of McMorris and his colleagues to investigate the relation between exercise-induced arousal and cognitive test performance. The conclusions drawn by the investigators may need to be tempered, however. It is probably the case that McMorris and his colleagues are correct in their assertion that the cognitive tests they developed have face validity. Considerable effort was taken to enlist the assistance of expert soccer players to develop play scenarios that reflected game-like situations. There is, however, a need for these investigators to demonstrate that their measures of cognitive performance possess not only face validity but also validity for change. A fundamental requirement of an interpretable dependent measure is that the measure adequately reflects changes that are brought about by the manipulation of an independent variable. Lipsey (1990, p. 100) describes two conditions that threaten a measure's validity for change. The first is the use of scaling procedures that are too gross to detect change. The second is a floor or ceiling effect that restricts changes that are produced by an independent variable.

There is reason to suspect the decision-making measures developed by McMorris lack sensitivity to change, both because of scaling properties and because of ceiling effects. In four experiments, subjects were given only 10, 4-choice decision problems during rest, moderate exercise, and vigorous exercise. Thus, for every evaluation a subject received a single score between 0 and 10. It is quite possible that the test's scaling properties limited the ability of the exercise intervention to produce a change. Problems associated with measurement scaling are compounded by the small sample sizes in these studies. Group sizes of 10 or less were reported in most studies. Recall that Tenenbaum et al. (1993) found that aerobic exercise improved handball players' accuracy of decision making. The scores obtained by each of the 118 participants in this study could range between 0 and 190. Further, the cognitive task discriminated among handball players judged as having low, medium and high experience. Players with high and medium experience demonstrated significantly better performance during exercise than players with low experience. Consider, also, that the cognitive task developed by McMorris and Graydon (1996a) and used in several subsequent studies (McMorris & Graydon, 1996b, 1997b; McMorris et al., 1999) failed to discriminate between experienced and inexperienced soccer players' decision-making abilities. It might be expected that a sensitive sport-specific test of decision making would differentiate players who differ in playing experience. However, both experienced and inexperienced players performed virtually identically during initial testing. Thus, the lack of agreement between the results obtained by Tenenbaum et al. (1993) and McMorris may be explained in terms of the sensitivity of the dependent measure to detect the effect of the exercise intervention.

McMorris and Graydon (1996b) acknowledged that interpretations of the outcome of their studies may have been compromised by ceiling effects and they addressed this possibility. The complex problem-solving task they developed did, in fact, reduce the level of participants' performance. However, these manipulations do not reduce the degree to which scaling problems and subject group size compromised their research findings. The findings of McMorris and his colleagues, while important, would be strengthened considerably if a criterion-group contrast confirmed the sensitivity of their response accuracy measurement procedure. It is common in the social and behavioral sciences to determine a measure's sensitivity by comparing the performance of two groups known to differ on the characteristics that the intervention is expected to change (e.g., high and low soccer skills). The magnitude of the difference between the groups should be in the range that which would be expected of a valid treatment effect difference (Lipsey, 1990, p. 104). Thus, it remains to be determined whether exercise influences both response speed and response accuracy.

The studies reviewed in this section indicate that the relation between exercise-induced arousal and cognitive performance is not simple. Compounding the difficulty in evaluating these tasks is the possibility that cognitive performance during and following exercise depends both on subjects' level of physical fitness and on their level of previous experience. Two studies conducted as direct tests of the inverted-U hypothesis suggest that the effects of exercise on cognitive function may depend on an individual's fitness level. Gutin and DiGennaro (1968b) failed to demonstrate that either a 1-min or a 5-min step-up exercise produced any change in subjects' simple mathematical computations over that observed during non-exercise conditions. However, 23 participants who had previously undergone training on the step-up task demonstrated significantly faster calculation speeds than 32 untrained subjects. Sjoberg (1980) determined that various intensities of cycling did not influence men's cognitive performance when measured either during or following exercise. However, the men of average fitness performed significantly better than men of low fitness during post-exercise test conditions. The investigators in both studies concluded that participants with greater fitness were better able to withstand the detrimental effects of physical stress than were less fit individuals.

The results of the Tenenbaum et al. (1993) study, which were described previously, demonstrated that experienced handball players performed complex-decision-making problems that simulated game situations significantly better than did less experienced players. Likewise, an intriguing study conducted by Delignieres et al. (1994) indicates that experience in sports that require rapid responding and rapid response selection influences subjects' performance during laboratory tests that assess speeded choice responses. The investigators contrasted the choice-reaction time performance of men and women who had either extensive histories of rapid decision making (fencers and fencing masters) and the performance of individuals who were equally physically fit, but not elite competitors. Participants performed 2-choice- and 4-choice-reaction tests during the last minute of four 4-min exercise periods. The exercise workloads were set at 20%, 40%, 60% and 80% of each individual's maximal aerobic power. Participants with fencing experience had significantly faster reaction times, with the greatest improvements in performance occurring while exercising at 40%, 60%, and 80% maximal aerobic power. Increases in reaction times were not accompanied by higher error rates, suggesting that improvement in reaction time was not due to the adoption of risky strategies. Non-fencers evidenced a significant lengthening of reaction time on both tests, with the greatest deterioration in performance occurring while exercising at 40%, 60%, and 80% maximal aerobic power. The investigators contrasted their findings to those obtained in several studies that had reported declines in cognitive performance as a function of high levels of exercise intensity. They suggested that participants' previous experience at making speeded decisions may help explain the lack of agreement that exists among other studies in the exercise literature.

The relation between exercise-inducted arousal and cognitive performance is complex. The lack of consistent and uniform laboratory results in support of a U-shaped relation between arousal and cognitive performance has led to considerable discussion of the construct of arousal and its measurement (see McMorris & Graydon, 2000). Compounding the difficulty of interpreting available research results is the possibility that an individual's performance may be influenced by a variety of factors; e.g., task type, experience, and level of physical fitness. Nevertheless, the data reviewed here provide compelling evidence that exercise modifies speed of information processing and evidence to suggest that exercise may, under some conditions, facilitate decision-making and complex problem solving. Clearly, additional systematic theory driven research is required prior to accepting or rejecting the validity of the inverted-U hypothesis. Recent technological advances in measuring brain function may provide researchers with sophisticated methods of linking physiological arousal to specific cognitive processes. Future research in this area of research may also benefit from recent theoretical developments generated in the field of neuropsychology.

2.3. Steady-state exercise and cognitive performance

The subjective psychological effects derived from bouts of aerobic exercise have been discussed extensively. A large body of research has examined the effects of aerobic exercise on affect, mood, and positive feelings of well-being (Scully, Kremer, Meade, Graham, & Dudgeon, 1998). Despite the considerable interest in understanding the effects of aerobic on affective states, relatively little systematic laboratory-based research has been conducted that examines the influence of aerobic exercise on cognitive processes. Further, the results of the studies that have been conducted are not consistent. Two of 15 studies reviewed failed to show a relation between aerobic exercise and cognitive function. Tomporowski et al. (1987) evaluated the effects of aerobic exercise on runners' free-recall memory. In the first of two experiments, 24 college students of average cardiovascular fitness ran on a treadmill at a speed that corresponded to 80% of their $VO_{2\max}$ for 50 min. Participants completed a series of paired-associate memory tests immediately following exercise. Memory performances of the exercisers did not differ from those of a non-exercise control group. In the second experiment, 12 student-athletes with very high levels of cardiovascular fitness completed memory tests immediately following a 50-min treadmill run. The memory performance of highly fit participants did not differ from the performance of individuals with average cardiovascular fitness. The authors concluded that aerobic exercise does not influence the encoding or retrieval of information from long-term memory, regardless of level of cardiovascular fitness.

Similarly, Travlos and Marisi (1995) assessed young men classified as high or low fit. Participants performed a 50-min cycling exercise regimen designed to be progressively more effortful every 10 min. A choice-reaction-time test and a test of concentration were administered during and following exercise. The exercise protocol had no effect on either measure and there were no substantial differences between the test performances of high- and low-fit individuals.

Eleven of the studies reviewed provide evidence that aerobic-type exercise of moderate intensity lasting less than 90 min in duration exerts a selective facilitative influence on cognitive functioning. There are data to suggest that aerobic exercise improves the operation of specific stages of information-processing, processes that are involved in complex problem solving, and attentional processes that are involved in response inhibition.

Submaximal bouts of exercise do not appear to affect perceptual mechanisms that are involved in the early stages of information processing; however, exercise does influence speed of decision making once information is encoded. Paas and Adam (1991) assessed the impact of two different 40-min submaximal exercise protocols on young adults' stimulus-identification and choice-reaction performances. Each protocol consisted of a baseline, warm up, exercise, and cool-down period. Under one exercise protocol, each participant cycled 5 min at 5% W_{max} (W_{max}), 10 min at 40% W_{max}, performed four 5-min cycling bouts of 2.5 min at 85% W_{max} and 2.5 min at 40% W_{max}, and cycled 5 min at 40% W_{max}. Under the other exercise protocol, each participant cycled 5 min at 5% W_{max}, 10 min at 40% W_{max}, 20 min at 75% W_{max}, and 5 min at 40% W_{max}. Cognitive tests were administered during exercise at each period of the protocol. The two exercise protocols had similar effects on participants' cognitive performance; choice-reaction times were significantly shorter during exercise and cool-down periods when compared to control conditions. Also, perceptual-task performance declined significantly during the exercise period but improved significantly during the cool-down period. A replication of this study was conducted by Adam et al. (1997). They employed only a single exercise condition consisting of a baseline period during which participants exercised at 5% W_{max}, a 10-min warm up period at 40% W_{max}, a 20-min exercise period at 75% W_{max}, and a 5-min cool down at 40% W_{max}. Participants' choice-reaction times were shorter during and following exercise; however, response accuracy was not influenced. In this study, the speed of participants' perceptual-task performance was significantly faster during both exercise and cool-down periods than during baseline periods. The authors suggest that the results of these two studies provide evidence of the positive effects of physical arousal on the allocation of attentional resources.

Several studies have found that bouts of aerobic exercise facilitate response preparation and activation of motor movement. Fleury et al. (1981) examined the impact of 45 min of cycling at 66% $VO_{2\,max}$ on young adults' performance of a coincidence-anticipation task that provided measures of temporal and spatial accuracy. The exercise period consisted of alternating 3-min bouts of cycling and resting. Participants' timed motor movement in conjunction with a moving target, and their performance on this task improved significantly following aerobic exercise. More recently, Fleury and Bard (1987) evaluated the effects of four different exercise protocols on young men's perceptual processing, motor timing, and letter-detection ability. The protocols included both anaerobic and aerobic exercise regimens. While maximal anaerobic exercise resulted in transient decrements in subjects' letter-detection performance, the exercise protocol in which participants ran for 30 min at a moderate pace and then at a faster pace until voluntary exhaustion led to significant improvements of subjects' performance both during a stimulus-detection task and during a coincidence-timing task.

A study by Arcelin et al. (1998) was designed to identify the locus of the effects of exercise during specific stages of information processing. They assessed young men's and women's 2-choice-reaction time performance while the participants cycled at 60% $VO_{2\,max}$. The information-processing conditions of the choice-reaction time tests were varied systematically. Stimulus intensity, signal-response compatibility, and time uncertainty were manipulated. Exercise influenced performance only during time uncertainty manipulations, suggesting that the primary influences of exercise are exerted in the response-preparation stage of processing. The authors' posited that exercise improves performance directly by affecting motor-preparation functions and indirectly by preparing the individual to respond to incoming sensory information.

The facilitative effects of aerobic exercise are seen not only during the performance of simple laboratory reaction time tasks, but also during complex problem-solving tasks. Marriott et al. (1993) assessed high- and low-skill soccer players' decision-making performance at rest, following an initial 45-min period of running, and then again following a second 45-min period of running. The investigators attempted to simulate the game-like exercise demands placed on soccer players; the treadmill speed elicited heart rates of approximately 157 beats min^{-1} throughout the exercise period. Participants were presented a series of 20 slides that depicted game scenarios. Each slide was presented for 20 s during which time each participant was asked a series of questions concerning the play. Subjects' responses were recorded and later evaluated by a panel of experts. The decision-making performance of both high- and low-skill participants was facilitated following 45 min of exercise; however, only low-skilled players' improvement was found to be statistically significant. After 90 min of exercise, high-skilled players' continued to make better decision than during rest, but not significantly so; low-skilled players' level of decision making declined significantly from the level exhibited following the first 45-min run. These results were interpreted as providing evidence for the mediating effect of playing experience on the soccer players' decision-making abilities.

Heckler and Croce (1992) administered a series of addition and subtraction problems, similar to those used by Gutin and DiGennaro (1968b), to groups of young women who differed in their level of cardiorespiratory fitness. Participants performed the tests at rest, following a 20-min run, and following a 40-min run at speeds that corresponded to 55% $VO_{2\,max}$. The problem-solving tasks were administered immediately, 5 min, and 15 min after each exercise bout. The exercise protocols facilitated participants' problem-solving speed during the three post-exercise test periods, with no loss in accuracy. Exercise differentially influenced the performance of the two groups; high-fit women's performance was improved following 20 and 40 min runs, low-fit women's performance improved only follow a run of 20 min.

The effects of a single bout of aerobic exercise on young women's higher-order thinking were assessed by Gondola (1987). Three tests of divergent thinking and problem solving were administered to 21 young women following a 20-min dance class and to another 16 women who did not exercise. An alternate use test provided flexibility of thinking measures and a consequences test provided measures of idea expression and originality of thinking. Women who exercised had significantly higher scores on all three measures than did non-exercisers. The author interpreted these findings as indicative of the beneficial effects of aerobic exercise on creativity. Although this was a field-research study with methodological shortcomings, the results obtained were robust and merit evaluation in this review.

Several studies demonstrate that response inhibition is facilitated by aerobic exercise. Response inhibition is the ability to withhold making a response when one is expected to do so. It involves the ability to selectively suppress irrelevant information in working memory in order to respond adaptively to the context of the current situation (Zacks & Hasher, 1994). Response inhibition is viewed as critical to adaptive functioning.

Hogervorst et al. (1996) conducted a study in which 15 highly trained triathletes and competitive cyclists completed a number of cognitive and psychomotor tasks prior to and following a 60-min simulated time trial. Participants pedaled at rates ranging between 75 and 100 rev min^{-1} and maintained levels of exertion that ranged between 75% and 85% $VO_{2\,max}$. The cognitive battery included three reaction-time tests (simple reaction time, 3-choice-reaction time, and incompatible 3-choice-reaction time), a finger-tapping test, and a short version of the Stroop Color-Word test (40 items of each of the three Stroop subtests). Exercise had a positive facilitative effect on simple reaction time, but not on choice-reaction time measures or finger-tapping rates. Exercise, however, improved participants' performance on a task that required the inhibition of a learned response; the time required to complete the Stroop Color-Word interference subtest decreased significantly. Data collected during a subsequent testing session reinforced the finding that the subjects' improved Stroop performance was due to exercise.

Similar results were obtained by Tomporowski et al. (submitted for publication). They assessed the effects of 40-min bouts of aerobic exercise and the effects of an oral cold medication on men's performance of the Paced Auditory Serial Addition Task, which, like the Stroop task, provides an index of the ability to refrain from making a previously learned response. Each subject performed two test sessions. In one session, he performed the cognitive task 60 min after ingesting medication and again after 40 min of cycling at 60% $VO_{2\,max}$; in the other session, he performed the cognitive test following ingestion of a placebo and again after 40 min of exercise. Participants' response inhibition increased significantly following ingestion of the cold medication and remained heightened following exercise. Importantly, response inhibition was unaffected by placebo but increased significantly following exercise. The investigators hypothesized that both exercise and the stimulant properties of the cold medication influence attentional processes that are important in gating distracting information from entering working memory.

An applied research study conducted by Lichtman and Poser (1983) also provides evidence for the effects of aerobic exercise on response-inhibition processes. They evaluated the effects of an aerobic jogging program on young adults' Stroop task performance. Sixty-four students were assigned randomly to participate in an aerobic exercise program or a hobby class. The Stroop task was administered to a subgroup of 10 students in each group. The participants performed the word naming, color naming, and color-word portions of the Stroop task prior to and immediately following exercise activities or hobby activities. The two groups did not differ in the number of items named during the pre-test; however, members of the exercise group named significantly more color names and color-word names than members of the hobby activity group.

People often report that their ability to concentrate and think clearly improves after bouts of aerobic exercise. Response-inhibition tasks constitute a laboratory analogue for the construct of mental concentration. Optimal performance during a response-inhibition task requires focusing attention on multiple stimulus–response alternatives and selecting responses that are consistent with the goals of the task.

The results of 11 of the 15 studies evaluated in this section indicate that submaximal aerobic exercise performed for durations between 20 and 60 min facilitates multiple cognitive processes that are critical to optimal performance and adaptive behavior. Following aerobic exercise people are better prepared to engage in action, concentrate, and solve complex problems than they are prior to exercise. It will be important for researchers to identify specific parameters of aerobic activity that facilitate cognitive function. Demonstrating that relatively short bouts of submaximal exercise have salutary effects on information processing and cognition has direct application to those involved in promoting educational and work environments conducive to optimal performance. Very little is known, for example, of the impact of periods of physical activity on young students' class attention and academic performance.

The results of two studies provide compelling evidence that prolonged submaximal exercise that leads to depletion of physiological energy stores compromises cognitive function. Cian and her colleagues performed a series of experiments that were prompted by the observation that thermal stress manipulations producing dehydration and more than a 2% loss in body weight result in significant declines in cognitive performance (Gopinathan, Pichan, & Sharma, 1988). The initial study contrasted the effects of passive thermal dehydration and exercise-inducted dehydration on eight young men's performance of a battery of cognitive tasks (Cian et al., 2000). During separate sessions, participants' body mass was lowered by 2.8% either by environmental heat exposure or by running on a treadmill at a speed corresponding to 60% $VO_{2\,\max}$. The dehydration phases were approximately 2 h in length. A control session required the participant to remain in a seated position and to maintain fluid hydration for 2 h. A battery of cognitive tests was administered 30 min after the dehydration period. The dehydration manipulations, when compared to control conditions, had no effect on participants' performance of a 4-choice serial discrimination task or a long-term memory task that measured free-recall and recognition memory. Both dehydration methods led to significantly poorer performance during a psychomotor tracking task and during a short-term memory digit-span test. Participants responded more slowly during a perceptual-discrimination task; their response accuracy, however, was not impaired. Approximately 60 min after administration of the cognitive test battery, participants performed an arm-crank exercise protocol wherein they rotated an arm ergometer at a rate corresponding to 85% $VO_{2\,\max}$ until fatigued (15–20 min). The cognitive test battery was administered 15 min following the termination of the arm-crank exercise. The additional exercise had no effect on the men's performance of the serial-reaction task, the perceptual-discrimination task, or the short-term memory task. Participants evidenced significantly poorer psychomotor tracking when dehydrated. Further, the men's performance of the long-term, free-recall memory test was impaired more when dehydration was induced by exercise than when it was induced passively.

Cian and his colleagues noted that the differential effects of exercise-induced dehydration and passive-heat dehydration on participants' long-term free-recall memory could have been the result either of dehydration or due to the arm-crank exercise protocol. Cian et al. (2001) addressed this issue directly in a study that isolated the effects of the two dehydration manipulations and the effects of re-hydration on cognitive performance. Seven young men completed five test sessions in which methods of dehydration and methods of fluid replacement were counterbalanced. Men's body weight was reduced by 2.8% over a 2 h period either by passive heat exposure or by running on a treadmill at a speed corresponding to 65% $VO_{2\,max}$. Participants remained hydrated during one session. A cognitive test battery was administered 30 min after the termination of the intervention. Neither dehydration procedure affected men's performance during choice-reaction, psychomotor tracking, or long-term memory tasks; however, dehydration resulted in a significant decline in short-term memory digit-span performance, and a lengthening of reaction time during a perceptual-discrimination task. The cognitive test battery was administered again $2\frac{1}{2}$ h later. Fluid replacement ameliorated the decline in short-term memory performance observed following dehydration manipulations. Further, lack of fluid replacement resulted in significant declines in men's free-recall memory test performance. The authors suggest that the dehydration produced by both exercise and by passive heat stress can impair men's response speed and memory performance, although it is not clear how fluid replacement impacts on cognitive performance.

In summary, the studies reviewed in this section provide evidence that acute bouts of steady-state exercise affect cognition. Continuous exercise that does not deplete physiological reserves is linked to improvements in response speed and response accuracy, and higher-order decision-making processes. Long bouts of exercise that lead to dehydration and its accompanying metabolic changes are associated with impaired information processing and cognition. This relation between steady-state exercise and cognition, however, can be influenced by such factors as the individual's level of physical fitness and his or her experience with the specific exercise.

3. General summary

A review was conducted of studies that examine the effects of acute bouts of exercise on cognitive functioning. Studies were separated into one of three groups on the basis of the focus of the experimental question investigated and on the basis of the intensity and duration of the exercise protocols employed. One group focused on the construct of fatigue and studies employed brief, maximal exercise protocols. A second group focused on the construct of arousal and studies employed both maximal and submaximal exercise protocols of short duration. The third group focused on the effects of submaximal exercise protocols of relatively long duration.

The question of central importance in this review is whether or not acute bouts of exercise exert systematic effects on cognitive function. An earlier review of the exercise literature by Tomporowski and Ellis (1986) failed to find empirical support for the notion that exercise has a significant positive influence on cognition. A recent meta-analysis of studies that assessed the effects of aerobic exercise on cognition led Etnier et al. (1997) to conclude that the impact of single bouts of aerobic exercise was limited only to improvements in participants' simple reaction time. Indeed, their analysis identified a negative relation between acute exercise and participants' performance on tasks that measured either choice or discriminant reaction time. These findings led Etnier and her colleagues to question the long-held belief that bouts of exercise benefit complex cognitive processes. A similar conclusion was reached in a recent review of the literature by McMorris and Graydon (2000). They posit that the beneficial effects of exercise-produced physical arousal are limited to increasing the speed of reaction time and facilitating individual's performance of well-learned, automatic tasks.

A number of well-controlled studies have been conducted since Tomporowski and Ellis' (1986) critique of the literature. The results of the empirical studies now available, when taken as a whole, suggest that acute bouts of exercise selectively facilitate multiple cognitive processes; exercise can, under certain conditions, enhance response speed and response accuracy, and it can facilitate cognitive processes that are central to problem-solving and goal-oriented action. The effect depends on the type and duration of exercise performed. Several studies designed to assess the arousal hypothesis and the majority of studies designed to assess the effects of steady-state exercise report improvements in participants' cognitive performance during and following periods of aerobic exercise performed at moderate intensities. Intense anaerobic exercise does not impair cognitive function significantly; however, submaximal aerobic exercise that leads to dehydration does compromise both information processing and memory functions.

Moderate levels of aerobic, steady-state exercise facilitates specific stages of information processing. Exercise does not influence directly those operations involved in the initial stage of processing. Studies consistently fail to find systematic effects of exercise on tasks that measure perceptual and sensory processing (Adam et al., 1997; Aks, 1998; Allard et al., 1989; Arcelin et al., 1998; Paas & Adam, 1991). Exercise does influence the decision-making stage of information processing. Faster choice responses have been observed both on simple (Adam et al., 1997; Brisswalter et al., 1995; Chmura et al., 1994; Delignieres et al., 1995; McGlynn et al., 1977; McGlynn et al., 1979; Paas & Adam, 1991) and complex tasks (McMorris & Graydon, 1996a,b, 1997a,b; McMorris et al., 1999) during and following exercise. In most cases, response speeds increase with no accompanying increase in error rates, suggesting that exercise is not simply altering participants' response criterion. Rather, exercise produces a condition during which individuals are able to perform both simple and complex tasks rapidly and efficiently (Gondola, 1987; Marriott et al., 1993;

Tenenbaum et al., 1993). Studies that employ tasks that measure response inhibition provide compelling evidence for the influence of exercise on working memory. Acute bouts of exercise improve the ability to block irrelevant information and to select and respond to task relevant information (Hogervorst et al., 1996; Lichtman & Poser, 1983; Tomporowski et al., submitted for publication). While exercise alters working-memory processes, it does not influence retrieval of information from long-term memory (Cian et al., 2000, 2001; Sjoberg, 1980; Tomporowski et al., 1987). Exercise has clear effects on the response-preparation stage of information processing. The capacity to mobilize and to time movement patterns is enhanced during and following bouts of steady-state aerobic exercise (Arcelin et al., 1998; Fleury & Bard, 1987; Fleury et al., 1981).

There are, of course, exceptions to the generalizations proposed. However, the conclusions drawn are bolstered when the results of empirical studies are evaluated in the context of contemporary energetic models of cognition. These theories attempt to capture the relation among the components of the information-processing system, the allocation of energy that is involved in mental operations, and the guidance functions of executive processes (see Molen van der, 1996, and Sanders, 1998, for reviews). A cognitive-energetic model proposed by Sanders (1983) (Fig. 1) emphasizes a relation among three levels of mental operations: a computational level, an executive control level, and an energy pool level. Computational processes include stimulus encoding, the storage and retrieval of information from interconnected memory structures, response selection, and response programming. The mechanistic activities of computational processes and resultant behavior are guided by processes that are taking place at the executive control level, where goal-directed, purposeful actions are formulated. The executive function addresses discrepancies that may exist between an organism's desired state and actual state. The executive processor evaluates discrepancies in terms of goals that can be attained via action. The role of executive processing is to plan, initiate, and monitor actions. The direction and intensity of those actions are determined by the allocation of resources that are present in three pools of energy: the effort pool, which determines the overall motivational state of the organism; the activation pool, which determines

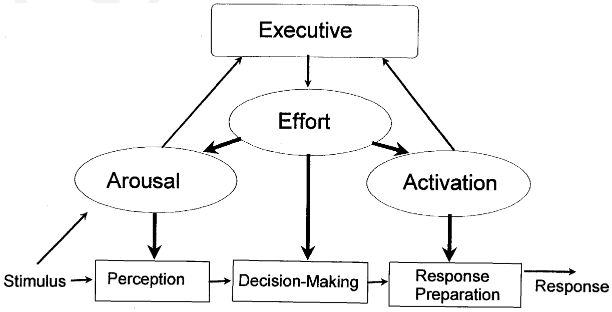

Fig. 1. Diagram of a simplified version of Sanders' (1983) cognitive-energetic model of human information processing (adapted from Jones and Hardy, 1989).

the resources that will be allocated by the organism to meet the demands that are encountered in the process of attaining specific goals; and the arousal pool, which is activated both by the effort pool and by stimulus input factors. The arousal pool responds in a phasic manner to variations in the quantity and quality of incoming sensory information. The allocation of energy from the arousal pool is reflected behaviorally through the speed at which an organism responds to novel stimuli or warning cues. The activation pool is affected by the allocation of effort resources and by motor-movement programming and the execution of actions. The activation pool responds in a tonic manner and is reflected behaviorally in the extent to which actions are sustained over time.

Sanders' (1983) model provides a coherent framework to identify both processes that are facilitated by exercise and processes that are not affected by exercise. Consider, for example, the experiment conducted by Arcelin et al. (1998), which was designed as a direct test of Sanders' model. In their study, the information-processing demands of a 2-choice-reaction time test were varied systematically while participants exercised. The intent of the study was to identify the locus of the effects of exercise on specific computational processing stages. Exercise had a selective effect on information processing; it interacted with performance only during time uncertainty manipulations. The authors interpreted these results to mean that exercise selectively affects the activation of specific pools of attentional resources and that the primary influences of exercise are exerted on response preparation. Exercise is presumed to lead to an allocation of resources that adjusts or 'fine tunes' the motor responses required for optimal performance. The authors evaluated participants' response patterns and posited that the effects of exercise are not limited to only one information-processing stage, however. They suggest that exercise improves performance directly by affecting motoric functions and also improves performance indirectly through other aspects of information processing. The authors infer that exercise also prepares or primes the individual to respond to incoming sensory information. The inferences made by Arcelin and his colleagues are corroborated by many of the studies evaluated in the present review.

The empirical data provides compelling support for the view that aerobic exercise can facilitate cognitive functioning. Acute bouts of moderately intense exercise are hypothesized to function in a manner similar to that of psychostimulant drugs, which do not influence directly the computational processes that are involved in information processing. Rather, they produce changes in state processes that are responsible for the allocation of attentional resources. [1] Future research will be required to test this hypothesis, however. The change in state processes brought about by acute exercise would be expected to be transitory. Only a few studies have examined the duration over which acute exercise affects cognitive processing. Heckler and Croce (1992) observed that participants' cognitive performance remained

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[1] See Sergeant (2000) and Sergeant et al. (1999) for examples of the application of Sanders' (1983) model to the study of psychostimulant drugs and their effects on children with attention deficit hyperactivity disorder.

heightened when measured immediately, 5 min, and 15 min following exercise. However, little is known of the time course of the impact of exercise on cognitive functioning. Exercise is known to produce increased plasma levels of such neurohormonal substances as epinephrine and norepinephrine, which have been linked to cognitive function (Chmura et al., 1994). The rate of production of these substances and the length of time they circulate in the blood stream differs for short bouts (Hughson, Green, & Sharratt, 1995; Kjaer, 1989) and steady-state bouts of exercise (Rowell & Shepherd, 1996). Thus, there is reason to believe that the length of time that exercise will influence cognitive function will depend on its intensity and duration.

The magnitude of the acute effects of exercise on cognitive function is expected to interact with a variety of individual difference variables. Several of the studies reviewed reported that the impact of exercise on performance depended on participants' level of physical fitness or their level of experience. It will remain for future research to determine the role that long-term physical fitness training has on the facilitative effects of acute bouts of exercise. Several theorists predict that an individual's response to an acute bout of exercise will be enhanced by improving his or her level of physical fitness (Dienstbier, 1989, 1991; Sothman, Hart, & Horn, 1991; Stones & Kozma, 1988).

The conclusions presented here differ from those published recently by Etnier et al. (1997) and McMorris and Graydon (2000). It was proposed in both of these reviews that the effects of acute bouts of exercise are limited to the facilitation of speed of responding during the execution of simple tasks and that exercise has little influence on complex-decision-making or problem-solving performance. There are a number of methodological issues that may explain the differences between the conclusions drawn in this review and those of other reviewers. Etnier et al. (1997) analyzed an assortment of experimental, quasi-experimental, correlational, and field-research studies. The exercise interventions employed in these studies varied extensively and included such activities as isometric muscle tension, acute bouts of exercise, movement education programs, and aerobic training programs. The cognitive tests used in these studies also varied considerably and included psychometric inventories, motor-movement tests, and information-processing tests. Many of the studies selected for analysis were drawn from research that addressed educational, life span, and developmental disability issues. Further, the review included only nine of the 43 studies evaluated in the present review. McMorris and Graydon (2000) selected for their review only studies that examined the arousal hypothesis and could provide comparisons among participants' cognitive performance at rest and at two or more levels of exercise. As a result, several studies that examined the effects of steady-state aerobic exercise were not evaluated. Further, the authors placed considerable emphasis on research conducted in their own laboratory, which, as discussed earlier in this review, may be problematic. The strategy used in the present review, which was to classify and examine groups of empirical research studies in terms of an established theory of cognitive function, illuminates how acute exercise influences cognition and it helps explain why previous reviews of the exercise literature have failed to detect a clear relation between exercise and cognition.

References

Adam, J. J., Teeken, J. C., Ypelaar, P. J. C., Verstappen, F. T. J., & Paas, F. G. W. (1997). Exercised-induced arousal and information processing. *International Journal of Sport Psychology, 28*, 217–226.

Aks, D. J. (1998). Influence of exercise on visual search: Implications for mediating cognitive mechanisms. *Perceptual and Motor Skills, 87*, 771–783.

Allard, F., Brawley, L., Deakin, J., & Elliot, F. (1989). The effect of exercise on visual attention performance. *Human Performance, 2*, 131–145.

Arcelin, R., Brisswalter, J., & Delignierres, D. (1997). Effects of physical exercise duration on decision-making performance. *Journal of Human Movement Studies, 32*, 123–140.

Arcelin, R., Delignieres, D., & Brisswalter, J. (1998). Selective effects of physical exercise on choice reaction processes. *Perceptual and Motor Skills, 87*, 175–185.

Bard, C., & Fleury, M. (1978). Influence of imposed metabolic fatigue on visual capacity components. *Perceptual and Motor Skills, 47*, 1283–1287.

Berger, B. G. (1996). Psychological benefits of an active lifestyle: What we know and what we need to know. *Quest, 48*, 330–353.

Brisswalter, J., Durand, M., Delignieres, D., & Legros, P. (1995). Optimal and non-optimal demand in a dual-task of pedaling and simple reaction time: Effects on energy expenditure and cognitive performance. *Journal of Human Movement Studies, 29*, 15–34.

Callaway, E. (1983). The pharmacology of human information processing. *Psychophysiology, 20*, 359–370.

Chmura, J., Nazar, K., & Kaciuba-Ulscilko, H. (1994). Choice reaction time during exercise in relation to blood lactate and plasma catecholamine threshold. *International Journal of Sports Medicine, 15*, 172–176.

Cian, C., Barraud, P. A., Melin, B., & Raphel, C. (2001). Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *International Journal of Psychophysiology, 42*, 243–251.

Cian, C., Koulmannn, N., Barraud, P. A., Raphel, C., Jimenez, C., & Melin, B. (2000). Influences of variations in body hydration on cognitive function: Effects of hyperhydration, heat stress, and exercise-induced dehydration. *Journal of Psychophysiology, 14*, 29–36.

Cote, J., Salmela, J. H., & Papthanasopoloulu, K. P. (1992). Effects of progressive exercise on attentional focus. *Perceptual and Motor Skills, 75*, 351–354.

Delignieres, D., Brisswalter, J., & Legros, P. (1994). Influence of physical exercise on choice reaction time in sports experts: the mediating role of resource allocation. *Journal of Human Movement Studies, 27*, 173–188.

Dienstbier, R. A. (1989). Arousal and physiological toughness: Implications for mental and physical health. *Psychological Review, 66*, 84–100.

Dienstbier, R. A. (1991). Behavioral correlates of sympathoadrenal reactivity: The toughness model. *Medicine and Science in Sport and Exercise, 23*, 846–852.

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review, 66*, 183–201.

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. *Journal of Sport and Exercise Psychology, 19*, 249–277.

Fleury, M., & Bard, C. (1987). Effects of different types of physical activity on the performance of perceptual tasks in peripheral and central vision and coincident timing. *Ergonomics, 30*, 945–958.

Fleury, M., Bard, C., Jobin, J., & Carriere, L. (1981). Influence of different types of physical fatigue on a visual detection task. *Perceptual and Motor Skills, 53*, 723–730.

Gawron, V. J., French, J., & Funke, D. (2001). An overview of fatigue. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 581–595). Mahwah, NJ: Lawrence Erlbaum.

Gondola, J. C. (1987). The effects of a single bout of aerobic dancing on selected tests of creativity. *Journal of Social Behavior and Personality, 2*, 275–278.

Gopinathan, P. M., Pichan, G., & Sharma, M. A. (1988). Role of dehydration in heat stress-induced variations in mental performance. *Archives of Environmental Health, 43*, 15–17.

Gutin, B., & DiGennaro, J. (1968a). Effect of a treadmill run to exhaustion on performance of simple addition. *Research Quarterly, 39*, 958–964.

Gutin, B., & DiGennaro, J. (1968b). Effect of one-minute and five-minute step-ups on performance of simple addition. *Research Quarterly, 39*, 81–85.

Hancock, S., & McNaughton, L. (1986). Effects of fatigue on ability to process visual information by experienced orienters. *Perceptual and Motor Skills, 62*, 491–498.

Heckler, B., & Croce, R. (1992). Effects of time of posttest after two durations of exercise on speed and accuracy of addition and subtraction by fit and less-fit women. *Perceptual and Motor Skills, 75*, 1059–1065.

Hogervorst, E., Riedel, W., Jeukendrup, A., & Jolles, J. (1996). Cognitive performance after strenuous physical exercise. *Perceptual and Motor Skills, 83*, 479–488.

Holding, D. H. (1983). Fatigue. In G. R. J. Hockey (Ed.), *Stress and fatigue in human performance* (pp. 145–167). New York: John Wiley and Sons.

Hughson, R. L., Green, H. J., & Sharratt, M. T. (1995). Gas exchange, blood lactate, and plasma catecholamines during incremental exercise in hypoxia and normoxia. *Journal of Applied Physiology, 79*, 1134–1141.

Hull, C. L. (1943). *Principles of behavior*. New York: Appleton Century.

Isaacs, L. D., & Pohlman, E. L. (1991). Effects of exercise intensity on an accompanying timing task. *Journal of Human Movement Studies, 20*, 123–131.

Kjaer, M. (1989). Epinephrine and some other hormonal responses to exercise in man: with special reference to physical training. *International Journal of Sports Medicine, 10*, 2–15.

Levitt, S., & Gutin, B. (1971). Multiple choice reaction time and movement time during physical exertion. *Research Quarterly, 42*, 405–411.

Lichtman, S., & Poser, E. G. (1983). The effects of exercise on mood and cognitive functioning. *Journal of Psychosomatic Research, 27*, 43–52.

Lipsey, M. W. (1990). *Design sensitivity: Statistical power for experimental research*. Newbury Park, CA: Sage.

Marriott, T., Reilly, T., & Miles, (1993). The effect of physiological stress on cognitive performance in a simulation of soccer. In T. Reilly, J. Clarys, & A. Stibbe (Eds.), *Science and football II* (pp. 261–264). London: E and FN Spon.

McGlynn, G. H., Laughlin, N. T., & Bender, V. L. (1977). Effect of strenuous to exhaustive exercise on a discrimination task. *Perceptual and Motor Skills, 44*, 1139–1147.

McGlynn, G. H., Laughlin, N. T., & Rowe, V. (1979). The effects of increasing levels of exercise on mental performance. *Ergonomics, 22*, 407–414.

McMorris, T., & Graydon, J. (1996a). The effects of exercise on the decision-making performance of experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport, 67*, 109–114.

McMorris, T., & Graydon, J. (1996b). Effects of exercise on soccer decision-making tasks of differing complexities. *Journal of Human Movement Studies, 30*, 177–193.

McMorris, T., & Graydon, J. (1997a). Effects of exercise on the decision making of soccer players. In T. Reilly, J. Bangsbo, & M. Hughes (Eds.), *Science and football III* (pp. 279–284). New York: E and FN Spon.

McMorris, T., & Graydon, J. (1997b). Effect of exercise on cognitive performance in soccer-specific tests. *Journal of Sports Sciences, 15*, 459–468.

McMorris, T., & Graydon, J. (2000). The effect of incremental exercise on cognitive performance. *International Journal of Sport Psychology, 31*, 66–81.

McMorris, T., & Keen, P. (1994). Effect of exercise on simple reaction times of recreational athletes. *Perceptual and Motor Skills, 78*, 123–130.

McMorris, T., Meyers, S., Macgillivary, W. W., Sexsmith, J. R., Fallowfield, J., Graydon, J., & Forster, D. (1999). Exercise, plasma catecholamine concentrations and performance of soccer players on a soccer-specific test of decision making. *Journal of Sports Sciences, 17*, 667–676.

Molen van der, M. W. (1996). Energetics and the reaction process: Running threads through experimental psychology. In O. Neumann & A. F. Sanders (Eds.), *Handbook of perception and action: Vol. 3. Attention* (pp. 229–276). New York: Academic Press.

Morgan, W. P. (1984). *Coping with mental stress: The potential and limits of exercise interventions (Final report)*. Bethesda, MD: NIMH.

Morgan, W. P., & O'Connor, P. J. (1988). Exercise and mental health. In R. K. Dishman (Ed.), *Exercise adherence: Its impact on public health* (pp. 91–121). Champaign, IL: Human Kinetics.

Oxendine, J. B. (1984). *Psychology of motor learning*. Englewood Cliffs, NJ: Prentice Hall.

Paas, F. G. W. C., & Adam, J. J. (1991). Human information processing during physical exercise. *Ergonomics, 34*, 1385–1397.

Proctor, R. W., Reeve, E. G., & Weeks, D. J. (1990). A triphasic approach to the acquisition of response-selection skill. In G. H. Bower (Ed.), *The psychology of learning: Advances in research and theory* (pp. 207–240). New York: Academic Press.

Raglin, J. S. (1997). Anxiolytic effects of physical activity. In W. P. Morgan (Ed.), *Physical activity and mental health* (pp. 107–126). Washington, DC: Taylor and Francis.

Reilly, T., & Smith, D. (1986). Effect of work intensity on performance in a psychomotor task during exercise. *Ergonomics, 29*, 601–606.

Rowell, L. B., & Shepherd, J. T. (Eds.). (1996). *Handbook of physiology, Section 12: Exercise: Regulation and integration of multiple systems*. New York: Oxford University Press.

Salmela, J. H., & Ndoye, O. D. (1986). Cognitive distortions during progressive exercise. *Perceptual and Motor Skills, 63*, 1067–1072.

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica, 53*, 61–97.

Sanders, A. F. (1998). *Elements of human performance*. Mahwah, NJ: Lawrence Erlbaum.

Scully, D., Kremer, J., Meade, M. M., Graham, R., & Dudgeon, K. (1998). Physical exercise and psychological well being: a critical review. *British Journal of Sports Medicine, 32*, 111–120.

Sergeant, J. (2000). The cognitive-energetic model: an empirical approach to attention-deficit hyperactivity disorder. *Neuroscience and Behavioral Reviews, 24*, 7–12.

Sergeant, J. A., Oosterlaan, J., & van der Meere, J. (1999). Information processing and energetic factors in attention-deficit/hyperactivity disorder. In H. C. Quay & A. E. Hogan (Eds.), *Handbook of disruptive behavior disorders* (pp. 75–104). New York: Kluwer Academic.

Shephard, R. (1996). Habitual physical activity and quality of life. *Quest, 48*, 354–365.

Sjoberg, H. (1980). Physical fitness and mental performance during and after work. *Ergonomics, 23*, 977–985.

Sjoberg, H., Ohlsson, M., & Dornic, S. (1975). *Physical fitness, work load and mental performance*. Report Department of Psychology, University of Stockholm, No. 444.

Soames Job, R. F., & Dalziel, J. (2001). Defining fatigue as a condition of the organism and distinguishing it from habituation, adaptation, and boredom. In P. A. Hancock & P. A. Desmond (Eds.), *Stress, workload, and fatigue* (pp. 466–475). Mahwah, NJ: Lawrence Erlbaum.

Sothman, M. S., Hart, B. A., & Horn, T. S. (1991). Plasma catecholamines response to acute psychological stress in humans: Relation to aerobic fitness and exercise training. *Medicine and Science in Sports and Exercise, 23*, 860–867.

Stones, M. J., & Kozma, A. (1988). Physical activity, age, and cognitive/motor performance. In M. L. Howe & C. J. Brainerd (Eds.), *Cognitive development in adulthood: Progress in cognitive development research* (pp. 273–321). New York: Springer-Verlag.

Tomporowski, P. D., Armstrong, L. E., & Kane, G. (submitted for publication). Effects of acute exercise and cold medication on men's performance and workload ratings during the paced auditory serial addition test.

Tomporowski, P. D., & Ellis, N. R. (1986). The effects of exercise on cognitive processes: A review. *Psychological Bulletin, 99*, 338–346.

Tomporowski, P. D., Ellis, N. R., & Stephens, R. (1987). The immediate effects of strenuous exercise on free recall memory. *Ergonomics, 30*, 121–129.

Travlos, A. K., & Marisi, D. Q. (1995). Information processing and concentration as a function of fitness level and exercise induced activation to exhaustion. *Perceptual and Motor Skills, 80*, 15–26.

White, J. M., & Rumbold, G. R. (1988). Behavioral effects of histamine and its antagonists: a review. *Psychopharmacology, 95*, 1–14.

Wrisberg, C. A., & Herbert, W. G. (1976). Fatigue effects on the timing performance of well practiced subjects. *Research Quarterly, 47*, 839–844.

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *Journal of Comparative Neurology and Psychology, 18*, 459–482.

Zacks, R. T., & Hasher, L. (1994). Directed ignoring: Inhibitory regulation of working memory. In D. Dagenbach & T. H. Carr (Eds.), *Inhibitory processes in attention, memory, and language* (pp. 241–264). New York: Academic Press.