THE EFFECTS OF ACUTE EXERCISE AND CAFFEINE ON TEMPORAL GENERALIZATION by

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(Under the Direction of Phillip D. Tomporowski)

ABSTRACT

The primary purpose of this dissertation was to examine the effects of acute exercise on human information processing. A quantitative review of the literature on acute exercise and cognition demonstrated that information processing may be enhanced or impaired depending on when it is measured, the type of cognitive task used, and the type of exercise performed. During exercise, participants' cognitive performance was impaired, $\Delta = -0.14$, whereas following exercise there was a small improvement in cognitive task performance, $\Delta = 0.20$. Speeded mental processes were facilitated both during and following exercise, and memory storage and retrieval were enhanced following exercise. Cycling was associated with enhanced performance during and after exercise, whereas treadmill running led to impaired performance during exercise and a small improvement in performance following exercise. The review also revealed that empirical studies on the effects of acute exercise on interval timing were needed. The ability to accurately time short intervals is critical aspect of cognitive performance. Thus, a second purpose of this dissertation was to examine the influence of acute exercise on interval timing. Due to the widespread use of caffeine as an ergogenic agent, the effects of caffeine and exercise were also explored. Exercise and caffeine were examined as arousal manipulations within the context of

scalar expectancy theory, the leading contemporary theory of interval timing. Part of the success of this theory is the ability to predict how changes in arousal states influence timing behavior. If the basis of a duration judgment is timed under a normal state, then increasing the clock speed so that the current duration is timed with a faster clock will result in a behavioral shift relative to a condition where both durations are timed with the clock running at the same speed. It was hypothesized that acute exercise and caffeine would have effects on timing tasks similar to other manipulations that increase clock speed. As predicted, when a reference memory was timed under a normal state, exercise resulted in a behavioral shift that consistent with a faster internal clock. The results of the caffeine manipulation (5mg/kg) illustrated the sensitivity of the timing system. The basis of the timing judgments was generated following the administration of caffeine and placebo. For each group, the current durations were compared to a reference duration that had been timed with the clock running at the same speed, effectively washing out any differences in timing performance for the caffeine and placebo groups. Evidence that the basis of the judgments were timed with a faster clock in the caffeine condition was present in the task performed after rest. The generalization gradient for timing behavior that was measured after a decrease in arousal shifted to right, consistent with more "ticks" being associated with the standard due to a faster clock speed. More research is needed to isolate the effects of caffeine on the internal clock.

INDEX WORDS: Cognition, Information Processing, Meta-Analysis, Temporal Generalization, Scalar Timing, Acute Exercise, Peak Oxygen Consumption, Caffeine, Arousal

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GENERALIZATION

by

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The notion that physical health can have a positive influence on mental acuity is present throughout recorded history. The ancient Roman saying, *mens sana in corpore sano*, is often interpreted to mean that only a healthy body can produce a healthy mind. Modern research has supported the relation between physical and mental health. In particular, studies have provided evidence for a link between physical exercise and mental functioning. Chronic exercise brings about changes in the brain that improve cognitive function (Cotman & Birchtold, 2002), contribute to healthy cognitive development (Sibley & Etnier, 2003), and play a role in healthy aging (Colcombe & Kramer, 2003).

Cognitive function also appears to be influenced by a single bout of exercise, although a consensus about this effect has been elusive. Researchers have typically manipulated the intensity or duration of physical exertion and measured cognitive performance at different levels or time points during and after exercise. The different approaches taken by researchers, coupled with the wide variation in outcome measures, have made efforts to summarize and synthesize research findings difficult. The common conclusion of narrative reviews on the topic is that the results are "mixed." A small but significant effect (ES = 0.16) of acute exercise has been reported in a systematic review, however, the methods used in this analysis permit limited conclusions. This will be discussed further in the section, "The Effects of Exercise-Induced Arousal on Cognitive Task Performance: A Meta-Regression Analysis."

A clear understanding of the relation between acute exercise and cognition is important for populations such as military and emergency response personnel, who make critical decisions

while under physical duress. The ability to process temporal information correctly is an important part of the decision making process. Time estimation is a cognitive construct with ties to attention, memory, perception, and representation (Glicksohn, 2001). Human time estimation has been the subject of much empirical study but timing studies have been rarely performed with participants under a physical load. Thus, the effects of acute exercise on the processes involved in timing are unclear. Several studies have demonstrated the link between timing and arousal and increasing physiological arousal through exercise is also likely to influence timing.

Statement of the Problem

The present state of knowledge about acute exercise and cognition does not allow researchers to make conclusions about the magnitude of the effect and the factors that influence it. A meta-analysis of the literature on this topic is needed to determine what cognitive changes occur during and following exercise and moderators that influence the relation. One purpose of this dissertation is to examine the effects of acute exercise on cognition using meta-analytic procedures. A second purpose is to focus on a critical aspect of cognitive performance, time estimation, and examine how it is influenced by acute exercise. This will be done within the context of the scalar expectancy theory, which proposes that the raw material for duration judgments comes from an internal clock of a pacemaker-accumulator type. Finally, the effects of caffeine administration prior to acute exercise will be explored.

Hypotheses

First hypothesis. A meta-analytic review of the experimental literature on the effect of acute exercise on cognition will reveal a small, positive effect on cognitive performance. The time at which cognitive tests were administered is expected to influence effect size, with larger effects expected during exercise as the length of the exercise bout increased and the effects

dissipating gradually following termination of exercise. This effect will be heterogeneous and moderated by characteristics of the participants studied and features of the research design.

Second hypothesis. An experimental study of the effect of acute exercise on timing performance will reveal significant differences between rest and exercise conditions. It is hypothesized that exercise will increase the speed of the participants' internal clock, increasing the subjective length of stimuli on a multiple-trial referenced temporal discrimination task (Penton-Voak et al., 1996). Shorter-duration stimuli will be identified as the standard, shifting the generalization gradient to the left. Furthermore, it is anticipated that exercise will offset the arousal-related lengthening of subjective estimates that occur towards the end of a testing session (Wearden, Pilkington, & Carter, 1999). In other words, the generalization gradients will not shift to the right as they do under non-exercise conditions.

Third hypothesis. Exercise will not influence timing performance on an episodic temporal generalization task, because the durations to be discriminated are only held briefly in working memory and will be timed with the same clock speed (Wearden, 2008). Also, it has been proposed that arousal manipulations (e.g. drugs, stress) affect timing due to their influence on the internal clock component of the scalar timing model (Penton-Voak et al., 1996). It is unclear whether exercise-induced arousal will affect timing in a similar manner or whether it may also influence the working memory component of the model. Evidence on the effects of exercise on working memory is inconsistent. Acute exercise is not expected to influence performance on working memory tasks (Random Number Generation, Operation Span) performed in temporal proximity to the scalar timing tasks. This will provide evidence for the specificity of exercise-induced arousal on the internal clock.

Fourth hypothesis. A randomized, controlled trial of the effects of caffeine administration on cognitive performance will reveal additive effects of exercise and caffeine on timing processes. Participants in the caffeine group in the exercise condition are expected to have the fastest internal clocks, and will therefore identify shorter stimuli as the standard to a greater extent than participants in the other conditions.

Statistical Analysis

Meta-analytic procedures will be used to quantify the magnitude and variability of the relation between acute exercise and cognition. The extent to which participant and design characteristics moderate the relation will be examined. Meta-analytic procedures are advantageous for several reasons: the studies included are selected based on standardized criteria, research results are summarized in a consistent manner, and small sample bias is avoided through weighting techniques. A macro (SPSS Inc., Chicago IL, version 16.0) will be used to calculate the aggregated mean effect size, the 95% confidence interval, and the sampling error variance using a random effects model (Lipsey & Wilson, 2001, pp. 208-212). A second macro will be used to analyze the moderators with a weighted least squares multiple linear regression to determine independent effects on variation in effect size. Moderators will be coded according to planned contrasts among levels, weighted by the within-subjects degrees of freedom, and recalculated with the random effects variance component added (Hedges & Olkin, 1985).

Several analyses will be necessary to evaluate the results of the first experimental study. The first analyses will examine the condition, stimulus duration, and interaction effects on the multiple-trial referenced timing task. The first analysis will consist of within-subjects 2 (condition: rest, exercise) by 2 (duration range: short, long) by 9 (stimulus duration: 142ms, 182ms, 234ms, 252ms, 300ms, 357ms, 385ms, 495ms, 635ms for the 300ms standard and

283ms, 364ms, 467ms, 504ms, 600ms, 715ms, 770ms, 989ms, and 1270ms for the 600ms standard) ANOVA with repeated measures on all factors. Performance of the test blocks for the 300ms and 600ms standard will also be analyzed separately using within-subjects 2 (condition: rest, exercise) by 9 (stimulus duration) ANOVAs with repeated measures on both factors. Another ANOVA will be performed on these data to evaluate subjective lengthening of durations across trial blocks. The proportion of responses from the 300ms and 600ms blocks will be collapsed at each of the comparison durations (142ms with 283ms, 182ms with 364ms, and so on). Performance across blocks of trials will be compared using a within-subjects 2 (Condition: rest, exercise) by 9 (Stimulus duration) by 6 (Block) ANOVA with repeated measures on all factors. The episodic temporal generalization task will be analyzed using a 2 (condition: rest, exercise) by 7 (stimulus multiplier: 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75) ANOVA with repeated measures on all factors.

For the Random Number Generation task, the turning point index, variability in phase lengths, and adjacency will be calculated as measures of inhibition. The updating function will be assessed through calculations of redundancy and mean repetition gap. Scores on these measures were compared using a 3 (condition: rest, first exercise bout, second exercise bout) by 2 (time: pre, during) ANOVAs with repeated measures on both factors. Finally, the operation span will be calculated for the tests administered prior to and after the resting control condition and the first exercise session. These scores will be compared using a repeated-measures 2 (condition: rest, exercise) by 2 (time: pre, post) ANOVA. Verbal estimates of the elapsed time will be converted into ratios (estimate/actual time), averaged for the exercise conditions, and compared using a a 2 (condition: rest, exercise) by 7 (estimate block: minutes 0-5, 6-10, 11-15, 16-20, 20-25) ANOVA with repeated measures on both factors.

Several different analyses will also be performed to evaluate the results from the second experimental study. The first analyses will examine the group, time, and interaction effects for the multiple-trial referenced timing task. These analyses will consist of a mixed model 2 (group: caffeine, placebo) by 2 (condition: rest, exercise) by 9 (stimulus duration: 142ms, 182ms, 234ms, 252ms, 300ms, 357ms, 385ms, 495ms, 635ms for the 300ms standard and 283ms, 364ms, 467ms, 504ms, 600ms, 715ms, 770ms, 989ms, and 1270ms for the 600ms standard) ANOVA with repeated measures on the condition and stimulus duration factors. Performance will also be examined independently for 300ms and 600ms standard blocks. Further analyses will compare temporal generalization performance on the task performed after the drug manipulation but prior to the exercise manipulation. Scores will be collapsed for the tasks performed before exercise and before rest. This analysis consisted of a 2 (Group: caffeine, placebo) by 2 (Duration Range: short, long) by 9 (Stimulus Duration) ANOVA with Group as a between subjects factor and repeated measures on the Duration Range and Stimulus Duration factors.

Delimitations

First Delimitation. The meta-analysis will report on the effects of acute exercise on cognition measured prior to, during, and following acute exercise. No attempts will be made to examine the effects of chronic exercise on cognition.

Second Delimitation. The experimental studies will not measure the effects of chronic physical activity on temporal generalization performance.

Definition of Terms

Physical Activity. Physical activity is any bodily movement produced by skeletal muscle that results in energy expenditure.

Acute Exercise. Acute exercise is a single, relatively short-lived bout of exercise.

Chronic Exercise. Bouts of exercise that are repeated on a regular basis over a period of time, typically defined in terms of the type of activity, intensity, duration, frequency per week, and time period (e.g. weeks, months).

Peak Oxygen Consumption. The peak rate at which oxygen can be consumed by and individual and utilized by working muscle during exercise; the estimated power or capacity of the aerobic system.

Cognition. All processes by which the sensory input is transformed, reduced, elaborated, stored, recovered, and used.

Temporal Generalization. A procedure in which the duration of individual stimuli are compared to a "standard" or reference duration. In humans, the response is typically in the form of a yes/no dichotomy. The proportion of *yes* responses is plotted against stimulus durations to construct a generalization gradient.

Scalar Timing. Behavior which conforms to the scalar properties of time, namely *mean accuracy*, the requirement that the internal "estimate" of some real time, *t*, is on average exactly equal to *t*, and *scalar property of variance*, the requirement that the standard deviation of time "estimates" varies linearly with their mean.

Overview and Organization

This dissertation proposal is organized into 5 chapters that will provide a background on the relation between acute exercise and cognition; report the results of a systematic, quantitative analysis of the relation between acute exercise and cognition to quantify the magnitude of the effect and examine moderating variables; provide a background on time estimation and scalar expectancy theory; examine the effect of acute exercise on the internal clock; explore the effects

of caffeine administration prior to exercise on the speed of the internal clock; and summarize the findings in terms of the proposed hypotheses.

Review of the Literature

The effect of exercise on cognitive function has been the subject of several hundred studies over the past 50 years. Researchers have examined the impact of chronic exercise training on cognition, as well as cognitive function during or after an acute bout of exercise. The studies of acute exercise and cognition have involved a wide array of exercise intensities, modalities, and durations. There has also been interest in the potential for exercise to remedy cognitive impairment during altered physiological states such as dehydration (e.g. Cian et al., 2000) and sleep deprivation (e.g. Englund, Ryman, Naitoh, & Hodgdon, 1985). Interactive effects of exercise and psychostimulants such as caffeine (Crowe, Leicht, & Spinks, 2006) and environmental conditions such as heat (e.g. Bunnell & Horvath, 1989) have also been studied.

Many of the studies in this area have involved reaction time as an outcome measure. Reaction time research has a long history. Among the pioneers of psychology, reaction time tasks were popular tools to study the speed of thought (Donders, 1868) and the dynamics of performance (Wundt, 1910). Standard reaction time tasks were used to investigate the effects of varying attentional states on cognitive performance. Visual and auditory simple and choice reaction time tasks are common in the exercise and cognition literature. For instance, in one early experiment (Fellows et al., 1926), the effects of fatiguing exercise on complex reaction time and auditory acuity were examined. Moderate intensity exercise has been shown to improve choice reaction time during an exercise bout (e.g. Adam et al, 1997; Audiffren et al., 2008).

Researchers in the area of human factors have influenced the study of acute exercise and cognition. The study of human factors is important because operators of human-machine systems

face increasing demands for monitoring and supervisory control due to automation. Perceptual tasks or vigilance tasks have been used to explore factors that might improve performance, such as ingestion of caffeine (see Koelga, 1993 for a review). Attempts have been made to determine whether acute exercise is a factor that can improve performance on these types of tasks. Exercise appears to influence performance on perceptual tasks such as critical flicker fusion threshold tasks, visual search tasks, and reaction time tasks.

The critical flicker fusion threshold is considered a quantitative index of cortical arousal and sensory sensitivity. It is a useful tool in exercise studies because it is responsive to exerciseinduced arousal. The critical flicker fusion task measures the point at which an individual perceives that a light flickering with increasing frequency has become fused (ascending threshold) and the point at which a fused light begins to flicker (descending threshold). A series of ascending and descending thresholds are typically averaged into an overall threshold score. Increases in overall threshold indicate that the individual can detect flicker longer and perceive flicker at a faster rate, indicative of improved sensory detection. Improvements in critical flicker fusion threshold after moderate and intense exercise have been reported in several studies (Al-Nimer & Al-Kurashy, 2007; Davranche & Pichon, 2005; Davranche, Burle, Audiffren, & Hasbroucq, 2005; Lambourne, Audiffren, & Tomporowski, 2010; Presland, Dowson, & Cairns, 2005; Shanmugam & Narayanan, 1973).

Thus, it has been established that acute exercise influences basic information processing tasks involving motor reaction time and lower-level, sensory type tasks such as the critical flicker fusion task. Other researchers have been interested in how acute exercise impacts complex, high-level processing, also known as executive processing or executive function (Alvaraz & Emory, 2006; Baddeley, 1986). Executive function was once thought to be a unitary,

high-level cognitive operation that regulated the operation of cognitive sub-processes during complex mental tasks (Baddeley, 1986; Norman & Shallice, 1986). More recently, executive function has been conceptualized as a non-unitary system that can be separated into at least 3 components: 1) mental set shifting; 2) inhibition of prepotent responses; and 3) updating the content of working memory (Miyake et al., 2000). Neurophysiological evidence supports the non-unitary nature of these functions as the neural networks that underlie these functions have been identified.

The effects of acute exercise on complex cognitive functions are unclear. The results of several recent studies utilizing executive function tasks have not been consistent, with some researchers reporting exercise-induced facilitation (Sibley, Etnier, & LeMasurier, 2006; Tomporowski et al., 2005), some reporting null effects (Coles & Tomporowski, 2007; Tomporowski & Ganio, 2006), and others reporting that acute exercise impaired performance on executive function tasks during exercise (Dietrich & Sparling, 2004). The Random Number Generation task was used in a recent study to examine the effect of exercise on the inhibition and updating components of executive function (Audiffren, Tomporowski, & Zagrodnik, 2008). Participants performed the task before, during, and after a bout of steady-state aerobic exercise. Exercise influenced inhibitory processes but not updating during exercise, and this effect dissipated rapidly once exercise had stopped. Exercise also caused participants to shift to a less effortful strategy to generate numbers, especially during the first few minutes of exercise. Together, these results suggest that exercise selectively influenced executive processes and the effects of exercise on certain higher-level processes are fairly transient.

Theoretical Framework

Why would acute exercise have an influence on cognition? Researchers have typically drawn on the arousal hypothesis and its variants to explain the relation between acute exercise and cognition. Many studies have examined whether the relation between cognitive performance and factors such as exercise intensity or duration is consistent with the traditional inverted-U hypothesis (Yerkes & Dodson, 1908). Researchers have also examined whether exercise-induced arousal narrows the range of external information that can be taken in, based on Easterbrook's cue utilization hypothesis. The results of these exercise studies have been explained in terms of unidimensional models of arousal (e.g. Kahneman, 1973). More recently, multi-dimensional models have been used to explain the effects of exercise on complex cognition.

Exercise has been considered an arousing stressor and the arousing effects of exercise on the peripheral and central systems have been well documented (Wittert, 2000). However, few investigators have provided a theoretical rationale for a causal link between exercise, arousal, brain catecholamines, and improvement in cognitive performance. Cooper (1973) was the first researcher to argue for this link based on evidence from human and animal studies. His claim was based on: increased synthesis of norepinephrine in the brain of rats during severe and prolonged forced exercise; increases in plasma catecholamine concentration during exercise; increases in brain noradrenergic activity during cortical activation; correlations between level of cortical arousal and activity of the reticular formation; and finally, the increase in activation of the reticular formation via somatosensory feedback due to limb movement during exercise. Extensive research has provided support for these arguments and as a result, "energetic" models compatible with this hypothetical explanation of the effects of acute aerobic exercise on cognition have been developed.

The first energetic model appeared in the book "Attention and Effort" by Kahneman (1973), which proposed that humans have a limited pool of resources to dedicate to a task. The amount of resources available depends on the level of arousal and the voluntary "effort" or attention allocated to the task. If exercise increases the arousal level, it increases the amount of resources available for cognitive task performance. However, exercise may also impair performance through interference. A high mental workload required by exercise can interfere with performance on a concomitant cognitive task. Low levels of interference are present at low values of workload, but interference may be severe at high values of workload. This type of interference would explain why performance on more demanding cognitive tasks has been impaired during exercise (e.g. Dietrich & Sparling, 2004).

The unidimensional nature of the resource pool in Kahneman's model has been criticized due to the confounding of arousal and effort. Sanders (1983) took a multidimensional approach to modeling cognitive and energetic interactions. In this model, arousal, activation, and effort influence specific stages of information processing. Arousal is linked to the feature extraction stage, activation to the motor adjustment stage, and effort to the response selection stage. In this model, acute exercise could increase both arousal and activation, which would modulate stimulus input and response output processes. If the cognitive task and the motor task both require mental effort, decision processes might also be affected via the effort mechanism.

Humphreys and Revelle (1984) took a multidimensional approach to explain the interactions among mental energy, personality, and motivation. This model includes three personality constructs (impulsivity, achievement motive, and trait anxiety) and six situational modifiers (incentives, feedback of success and failure, psychostimulant drugs, ego threat, time of day, and time on task). This model increases the predictive power about the effect of exercise on

cognition because it considers how personality traits interact with situational variables to change arousal level. For example, people with high trait anxiety generally have a higher level of arousal than people with low anxiety levels. Arousal-related individual differences in personality traits increase the between-subject variability in the effect size of exercise.

To account for the different pattern of effects seen on cognitive performance under stress and high workload, Hockey (1993, 1997) proposed a cognitive energetic model with a compensatory control mechanism. This mechanism protects performance and the maintenance of task goals in cognitively demanding situations. The model also includes an automatic control mechanism that operates without effort to regulate well-learned skills. During performance under stress, task decrements might not be overtly observed. However, latent breakdowns in performance can be detected that provide evidence for the regulatory mechanism. The latent breakdowns in performance include: impairment of secondary task components; shifting to less effortful strategies (e.g. less use of working memory, trading speed for accuracy); increased activation of physiological systems and affective responses (e.g. sympathetic stress responses); and fatigue after-effects evidenced by preference for low-effort strategies. This model can account for shifts in strategy that have been observed in studies of acute exercise (e.g. Audiffren, Tomporowski, & Zagrodnik, 2008).

The cognitive energetic models can be used to make predictions about how exercise will affect mental performance with varying degrees of accuracy. Common to these theories is the assumption that environmental stimulation changes performance by allocating energetical resources to prepare an individual to respond to task demands. The next chapter will provide a systematic review of the literature that has examined the relation between acute exercise and

cognitive performance. First, information about temporal processing and theories of timing behavior relevant to this dissertation will be discussed.

Temporal Processing

Time is one of the universal experiences of our lives (Ornstein, 1969). Scholars have been interested in the experience of time since the age of the ancient Greeks. The subjective experience of time was one of the important topics in early psychological research. For instance, William James dedicated a chapter of his book to the perception of time in "The Principles of Psychology" (1890, Chapter 15). Temporal processing has been the subject of a large body of research, and the psychophysical properties of timing in humans and animals have been fairly well-established (Allan, 1979). More recently, the neurobiological aspects of temporal processing have been explored (Rao, Mayer, & Harrington, 2001; Kesner & Hopkins, 2001; Eagleman et al., 2005).

Temporal experiences can be viewed in several ways depending on whether simultaneity, successiveness, temporal order, duration, or temporal perspective is examined (Block & Zakay, 1997). Judgments of duration are the most researched aspect of psychological time, likely due to their importance to environmental adaptation. Duration timing on the order of seconds and minutes is necessary for representing the past and present external environment. Temporal processing of extremely brief durations (10-50 ms) is often referred to as time perception, and the processing of time intervals in the range of seconds, minutes, or longer is referred to as time estimation (Rammsayer, 1993). Different mechanisms underlie these processes; time perception is fast and not accessible to cognitive control, whereas time estimation is cognitively mediated. Time estimation involves cognitive processes such as attention and memory, and these cognitive processes can be elucidated through estimates of duration (Block & Zakay, 1997).

Temporal information processing is an essential feature of central nervous system operation. The information that enters the central nervous system must be processed in terms of both temporal and spatial factors for the environment to be perceived correctly (Arteida & Pastor, 1996). Verification of the importance of time estimation is the fact that it develops early in life. The ability to perceive time has been shown to exist in 4-month-old infants (Colombo & Richman, 2002). Interestingly, no single sensory organ has been identified that underlies psychological time. Unlike circadian timing, which is mediated by the suprachiasmic nuclei, it appears that the perception of time is governed by a dynamic network cortical and subcortical activation that is associated with different components of temporal information processing (Rao et al., 2001).

The ability to produce accurate movements is also supported by precise temporal coordination of information processing and encoding. It is remarkable how proficient humans are at producing timed behaviors, evidence of which can be observed in sport performance. For instance, in a ball return in tennis, a player has a few tenths of a second to anticipate where the ball will land and how to position his body to hit it. The ability to execute accurately timed movements suggests that we have precise chronometers in our brains. However, the psychological experience of time is much less reliable, and depends on a multitude of diverse influences. For instance, physiological factors such as body temperature and fatigue can accelerate or decelerate the subjective passing of time. Other influences include mental disorders such as schizophrenia and depression, and drugs such as cocaine and LSD. A large body of research has been dedicated toward studying the psychological experience of time and factors that influence it.

Relatively few studies have examined timing during exercise. The study of timing during exercise may be of importance to certain populations. For instance, athletes engaged in high-speed sports such as soccer must properly time their actions to satisfy immediate and long-term goals. Emergency response personnel are required to react quickly and accurately to task demands while engaged in moderate to strenuous physical activity. The ability to correctly estimate the passage of time and correctly time responses is an important part of many physical and cognitive tasks, and errors in time-order estimation are associated with industrial accidents (Kantowitz & Sorkin, 1983).

Much of the research that has been performed on operator decision-making has been conducted in the laboratory with no physical demands imposed. Arousal and activation that result from physical exertion have energetic components that influence response capabilities (Sanders, 1983; Hockey, 1983), and there is evidence to suggest that timing processes would also be influenced by physical exertion. This will be addressed in the chapter, "The Effects of Acute Exercise on Temporal Generalization." First, however, background information will be provided about the methods used to study time estimation; factors that influence timing; theories and models of timing; and neuropsychological mechanisms of temporal processing.

Methods in the Study of Time Estimation

There are two primary research paradigms and several measurement methods used in experimental time estimation research. In the prospective paradigm, participants are aware that they will be asked to judge the duration of a time interval. This time interval is referred to as the *experienced duration* (Block, 1990) because the participant can intentionally encode temporal information as a part of the experience of the time interval. In the retrospective paradigm, a participant will judge the duration of a time interval after it has passed without advance

knowledge that he or she will be asked to do this (Block & Zakay, 1997). This time interval is referred to as the *remembered duration* because temporal information that may have been incidentally encoded is later retrieved from memory. It is assumed that different processes subserve prospective and retrospective judgments (Block, 1992; Hicks et al., 1976).

The different judgment methods include: 1) verbal *estimation* in which the participant verbally indicates the duration of a physically given time interval, 2) the method of *production*, where the participant is required to operatively produce a time interval verbally stated by the experimenter, 3) the method of *reproduction*, in which the participant operatively reproduces a time interval first demonstrated by the experimenter, 4) the method of *comparison*, in which the participant judges whether a time interval given by the experimenter is shorter or longer than a referent time interval, and 5) the method of *bisection*, where the participant decides if intervals of varying duration are more similar to a long standard or a short standard. Timing judgments differ based on the method used, for example, participants are more likely to judge an interval as being shorter than it actually is using the production and reproduction method. In contrast, individuals are more likely to overestimate a time interval by means of the verbal estimation method. The results from production and reproduction tasks are negatively correlated with the results from verbal estimation tasks (Boltz, 1994).

Thus, a variety of methods are available to researchers interested in the study of human timing. One advance in the area of time estimation has been the application of scalar expectancy theory (Gibbon, Church, & Meck, 1984) to timing in humans. Quantitative models of performance on timing tasks based on scalar expectancy theory have been developed and shown to accurately fit the data from human timing studies. Typically, scalar expectancy theory is applied to tasks such as bisection and temporal generalization rather than the classical timing

tasks such as verbal estimation, production, and reproduction (Wearden, 2007). Scalar expectancy theory will be described in greater detail in the section, "Theories and Models of Time Estimation."

Factors that Influence Time Estimation

People have a stable, internal clock tempo that can be altered by a variety of agents (Remoldi, 1951; Boltz, 1994). The changes differ based on a multitude of factors, such as the type of task and stimuli used to assess the temporal experience and individual difference factors such as sex. The different stimuli used in estimation tasks have an influence on subjective time estimation. Vierordt, a pioneer in the psychophysics of time, reported that short intervals of time tend to be overestimated, and long intervals tend to be underestimated in a prospective task (Vierordt, 1868). A review of the nature of the stimuli used in estimation tasks and the effects on duration estimates can be found in Fraisse (1984). In brief, filled intervals in which the stimulus is present through the interval are reproduced as longer durations than empty intervals. More intense sounds and lights are perceived as longer than less intense sounds and lights, and intensity has a larger influence on visual stimuli. Auditory stimuli seem longer than visual stimuli. Finally, the kappa effect describes the interaction between distance and time perception. If two points are placed sequentially on a computer screen, estimation of the presentation time is greater as the space between the points increases.

It has been consistently demonstrated that estimated time intervals decrease as the demands of the cognitive task increase. In a well-known study (Hicks, Miller, & Kinsbourne, 1976), participants were given a card-sorting task that varied according to the number of bits to be processed per card. When asked to judge the duration of the task, the time estimates decreased

monotonically with increased processing demands. This finding has been replicated using verbal tasks and encoding tasks that varied in processing demands (Zakay, Nitzan, & Glicksohn, 1983).

Attention also modulates the subjective perception of time (Chaston & Kingstone, 2004; Coull, Vidai, Nazarian, & Macar, 2004). When less attention is devoted to the temporal aspects of a stimulus, misperceptions of its duration are more likely. In a study of prospective timing and attention (Chaston & Kingstone, 2004), participants were asked to perform a non-demanding simple feature visual search task and an attention-demanding feature conjunction search. Set size on each task varied from 2 to 40 items for blocks of 40 to 60 trials. Participants provided written estimates of the task duration. As the attentional demands of the task increased, underestimates of the task duration increased.

Working memory capacity is another aspect of cognition that influences timing. Individuals with larger working memory capacities produce more reliable and accurate time estimates while engaged in a cognitively demanding task (Fink & Neubauer, 2005). Working memory is a limited-capacity resource that stores and manipulates information over brief time intervals, typically in the range of seconds to minutes. Individuals with larger working memory capacities can process a greater amount of information and are able to dedicate resources simultaneously to both the timing aspect and the processing aspect of a dual-task.

Theories and Models of Time Estimation

Several theories and models have been developed to explain the results of human time estimation studies. The different paradigms used to study time estimation have resulted in multiple models. Scalar expectancy theory was originally conceived as an animal model and is the leading theory of animal timing (Gibbon, 1977; Gibbon et al., 1984). As human analogue

experiments developed in the 1980's, scalar expectancy theory has also become the leading theory of human timing (Wearden, 1991; Penton-Voak, Edwards, Percival, & Wearden, 1996).

Memory and attention models. Typically, memory models are used to explain retrospective time estimates and attentional models are used to explain prospective estimates. In memory models, the remembered duration is directly related to the amount of information stored in memory during the time interval. This is referred to as the storage size hypothesis. The more information that is stored about an event, the larger the storage space and the longer the interval seems (Ornstein, 1969). Though this relation is confounded by stimulus complexity, the storage size hypothesis has received a lot of support (Hogan, 1978).

In contrast to memory models, the attentional models suggest that processing resources are shared between internal timer and non-temporal processing tasks. Thomas and Weaver (1975) proposed an attentional model of prospective timing in which an internal timer counts and stores temporal information. This mechanism requires attentional resources to operate, thus, nontemporal tasks compete for these resources. As these tasks become more demanding, more resources are diverted from timing and the experienced duration becomes biased (Glicksohn, 2001). Researchers have speculated that individual differences in working memory would cause individuals to have a different amount of resources to dedicate towards a prospective time estimation task. There is some evidence to support this notion, as higher-working memory individuals have been shown to produce more reliable and accurate time estimates while engaged in a cognitively demanding task (Fink & Neubauer, 2005).

The cognitive timer. Several researchers have proposed the existence of an internal clock (Triesman, 1963), alternatively described as a "pacemaker and accumulator" (Allan & Gibbon, 1991), or as a "family of chronometers" (Macar, 1993). The idea of the internal clock

rests on the assumptions that a timer exists whose purpose is to handle temporal information and that temporal information is processed by storing the number of time units that accumulate during a time interval. Other researchers have tried to incorporate attention into the internal clock model. In Fortin et al.'s (1993) model, for example, accumulation begins when attention turns the timer on via a gate. During non-temporal processing when the gate is off, the accumulation process is interrupted (Glicksohn, 2001).

Thus, attentional resources are utilized to engage both temporal and non-temporal information processing. The internal clock is also influenced by memory processes (e.g. Fortin & Breton, 1995; McCormack, Brown, Maylor, Richardson, & Darby, 2002; Ogden, Wearden, & Jones, 2008). Cognitive influences appear to be more pronounced for intervals longer than 500ms, leading some researchers to suggest that temporal processing of short intervals is based on an internal timing mechanism that is not accessible to cognitive control (Rammsayer, 1999), whereas the processing of longer intervals is cognitively mediated (Michon, 1985).

Scalar expectancy theory. Scalar expectancy theory, also known as the scalar timing theory, is the leading contemporary theory of time estimation. It was originally developed to explain the performance of rats and pigeons on reinforcement schedules that involved timed responses. Animal timing tasks then developed to test specific aspects of scalar expectancy theory such as temporal generalization (Church & Gibbon, 1982). The history and development of scalar expectancy theory in animal timing have been described in detail by Gibbon (1991).

Scalar expectancy theory is a mathematical model that describes the cognitive processes that occur when an organism is presented with a timing task. Conceptually, the model is similar to the internal clock model that was proposed by Triesman (1963). Internal clock models describe a mechanism that relates subjective temporal values to real time in an orderly manner.

The mechanism has been differentiated from periodic or oscillatory mechanisms because it is an interval timer that requires initiation by a signal. In contrast, periodic clocks like those responsible for circadian timing run continuously and are self-sustaining. Once an interval timer is started, it runs to completion and comes to rest on its own (Allan, 1998).

There are three information-processing stages that make up the scalar timing model (see Figure 2.1, adapted from Allan, 1998). The clock stage transforms subjective time into objective time. The pacemaker emits pulses at some mean rate, and a switch controlled by a timing signal tells the accumulator to count the pulses. The pulses sum as a linear function of real time. The next stage of the scalar timing model is the memory stage. There are two memory registers for the storage of temporal information in this stage. The accumulator loads directly into working memory, which provides a buffer for temporal information from the current trial. Reference memory stores information from previous trials and the comparator uses a decision rule to determine which response to make. Reference memory stores "important" times, such as those associated with reinforcement in animal studies and those identified as "standards" in human studies (Wearden & Grinrod, 2003). The decision rule depends on the type of timing task, but involves a ratio comparison of the information in working memory and the information in reference memory. A comparison rule described by Wearden (1992) is compatible with the generalization gradients found in experiments with humans. Humans respond, "yes," that durations are the same when $|s^*-t|/t \le b^*$, where s* is the sample drawn from long term memory, t is the just presented duration, and b^* is a threshold value which is variable from trial to trial. Variability in timing may arise from any of the components of the model (Allan, 1998).



Figure 2.1. Scalar timing model. (Allan, 1998)

Over the past few decades, scalar expectancy theory has been applied to timing in humans (see Allan, 1998 for a review). To conform to scalar expectancy theory, behavior must exhibit certain properties. The first property is based on the variance of timing measures, and the second is based on the property of mean accuracy. The scalar property of variance can be observed by computing a coefficient of variation and also by testing for superposition. The coefficient of variation statistic (standard deviation/mean) from timing measures can be used to demonstrate the scalar property, because this index remains constant even though the absolute duration timed varies (Wearden & McShane, 1988). A larger coefficient of variation value represents more variable temporal memories. Thus, there is a linear relation between the standard deviation of subjective time and mean subjective time. The standard deviation grows in proportion to the mean of the interval being timed. Superposition (also referred to as superimposition), the second method used to examine the scalar property of timing, occurs when measures of timed behavior from different absolute time values superimpose when graphed on the same scale. This is the reason the property is termed *scalar*. The scalar property of variance requires that timing sensitivity remain constant while the durations that are timed vary. This is a form of Weber's law.

The property of mean accuracy describes the linear variation of the mean measures of timed behavior. The average time intervals produced or estimated by individuals are typically in line with the time requirement or actual stimulus duration, respectively. When the observed timing behavior conforms to the scalar property of variance and the property of mean accuracy, it is known as empirical scalar timing. However, there are situations in which the underlying timing behaviors have scalar properties but the observed behavior does not, which is known as theoretical scalar timing (Lejeune & Wearden, 2006). These situations are the result of "additional processes" that moderate the underlying timing behavior (Wearden & Lejeune, 2007). For instance, when individuals use chronometric counting for timing, the mean accuracy property typically holds but the scalar property of variance will not (Wearden, 1991).

The temporal generalization method developed by Wearden (1992) results in a demonstration of superposition. In this method, the participant is presented with a stimulus of a certain duration that is identified as the "standard." Then, he or she is shown a series of comparison stimuli, some of which have a longer duration, some of which have a shorter duration, and some of which are equal in duration to the standard. When the proportion of stimuli identified as the standard is plotted against the duration, it results in a function that peaks at the standard and falls off as the durations become farther from the standard. This function is known as the temporal generalization gradient. Superposition has been shown to occur when humans
timed short duration intervals (400 to 700ms standards; Wearden, 1992), and longer intervals when chronometric counting was prevented (2, 4, 6, and 8s standards; Wearden, Denovan, Fakhri, & Howarth, 1997).

Superposition also occurs with variations in the parameters of temporal generalization procedures. In one example, researchers administered an "episodic" temporal generalization task that discouraged the development of a standard in reference memory (Wearden & Bray, 2001). The formation of a reference memory was prevented because the reference stimulus durations were never repeated, except by chance. For each trial, participants compared a sample stimulus duration to a comparison stimulus by responding *yes* or *no* to the question, "did the stimuli have the same duration?" The sample duration was selected from a range between 100ms to 1000ms, and the comparison stimulus was smaller than, larger than, or equal to the sample duration. The data from this task superimposed well, with the largest proportion of *yes* responses occurring on trials where the stimuli were the same duration. This indicated that scalar timing could still occur when the formation of a reference memory was improbable. Superposition has been also demonstrated during variations of stimulus duration, modality, and spacing (Wearden & Bray, 2001).

The functions produced with temporal generalization procedures tend to be asymmetrical. The asymmetry arises as a result of more *yes* responses occurring to stimuli longer than the standard than stimuli shorter by the same amount. The gradients also differ when chronometric counting is encouraged or prevented. The functions become more asymmetrical as the number of timing trials increases (Wearden, Pilkington, & Carter, 1999). Thus, behavioral changes during repeated testing in the temporal generalization paradigm entail longer intervals being

progressively identified as the standard. This phenomenon has been termed "subjective lengthening," and is correlated with subjective measures of arousal (Wearden, 1999).

The provision of feedback in studies of timing indicates that feedback plays a role in producing behaviors that conform to the properties of scalar timing. For instance, production tasks with feedback result in behaviors that conform to both the scalar property of variance and the property of mean accuracy, but production tasks without feedback do not (Wearden, 2003). According to Wearden et al. (1999), training humans to estimate or produce durations and then testing them later without feedback could be a useful method to test the effects of a drug state. If feedback was provided during the drug state, the participant could adjust for the faster or slower pacemaker speed, causing the drug effects to disappear.

One criticism of the scalar timing model is that the parts of the model can be adjusted to fit any data, creating problems of falsifiability (Wearden & Grindrod, 2003). One way to disambiguate the system is to manipulate one component of the model at a time while leaving everything else the same. This isolation method has been successful for manipulations that have attempted to change the speed of the pacemaker component of the internal clock. Pacemaker speed has been manipulated in rats using drugs (Maricq et al., 1981; Meck, 1983) and by presenting humans with a train of repetitive clicks or flashes (Treisman et al., 1990).

The memory level of the scalar timing model has received much less examination. However, several studies have examined human timing in the absence of reference memory (Jones & Wearden, 2004; Allan & Gerhardt, 2001; Rodriguez-Girones & Kacelnik, 1995; Wearden & Bray, 2001). As mentioned, Wearden et al. (2001) created an episodic temporal generalization task in which the standard stimulus varied randomly throughout the task. The generalization gradients still superimposed, which indicated that scalar timing could still occur in

the absence of a reference memory. This led timing theorists to propose that the source of scalar variability was the internal clock rather than the reference memory (Killeen & Taylor, 2000).

The decision level of the model has received the least attention but has been examined in a few studies (Wearden & Grindrod, 2003; Wearden & Culpin, 1998). To manipulate the decision level, different response payoffs were used while the stimuli to be timed remained identical. Encouraging identifications of the standard increased the response threshold in a manner consistent with the predictions of scalar expectancy theory. These studies showed that the decisional level of the model is an independent component that can be manipulated.

Neurophysiological Mechanisms of Temporal Processing

Unlike the mechanisms that are responsible for circadian rhythms, the neural basis of timing is relatively unknown. Thus, a question that remains about subjective time estimation is how this type of temporal information is processed in the brain. There has been some controversy in the literature about whether performance on different temporal tasks can be accounted for by an internal master clock rather than distinct, specific timing mechanisms (Rammsayer & Brandler, 2004). Several studies have supported the existence of a common timing mechanism that is involved in both temporal perception and production (Triesman, Faulkner, & Naish, 1992). A factor analysis (Rammsayer & Brandler, 2004) provided support for a common mechanism involved in duration discrimination, temporal generalization, and temporal order judgment. However, rhythm perception and perceived simultaneity and successiveness were not related to this mechanism and seemed to be controlled by processes unrelated to interval-based timing.

Certain brain areas have been implicated for involvement in time estimation tasks. It was once widely believed that the cerebellum was the critical brain structure responsible for time

estimation. However, recent neuroimaging studies have also implicated the basal ganglia and the right parietal lobe in a timing system. Event-related functional magnetic resonance imaging (fMRI) was used in a recent study to examine the functional anatomy of the attentional modulation of time estimation (Coull et al., 2004). Attention was manipulated parametrically by increasing task demands. The increases in task performance corresponded to increases in brain activity in the corticostriatal network. It has been consistently demonstrated that the striatum and the putamen in particular become activated in fMRI studies of timing, even those in which non-motor tasks are used (Nenadic et al., 2003; Rao et al., 2001).

In another influential study, the within-trial evolution of interval timing was examined (Rao et al., 2001). Activation in the basal ganglia occurred early in the trial and was uniquely associated with encoding time intervals. Cerebellar activity occurred later in the trial, suggesting an involvement of processes other than explicit timing. Later activation of the right dorsolateral prefrontal cortex occurred during comparison of time intervals. There appears to be dynamic network of cortical-subcortical activation associated with different aspects of temporal information processing.

Working memory relies on the same prefrontal and striatal brain structures as those involved in interval timing (Lustig, Matell, & Meck, 2005). Recent behavioral work supports the notion that this common neural substrate reflects a functional link. Robust interference effects are found for concurrent working memory and interval timing tasks, regardless of the different durations timed and the timing procedures used. The interference might be specific to the processing aspect of working memory, rather than the storage aspect (Fortin, 1999). Biologically-based models have been developed (Mattell & Meck, 2000; Matell, Meck, & Nicolelis, 2003) that emphasize the role of the striatum in processing temporal information. The

striatum detects and reacts to patterns of cortical firing that correspond to relevant stimulus events. One tenet of this model is that this "coincidence detection" function constitutes the deepseated link between working memory and interval timing (Lustig et al., 2005).

Dopamine has been implicated as a neurotransmitter involved in timing processes. Administration of a dopamine antagonist causes animals trained with reinforcement schedules to respond early (Baunez, Nieoullon, & Amalric, 1995; Meck, 1996). Similarly, humans who are administered haloperidol, a dopamine antagonist, are less accurate in making temporal discriminations (Rammsayer, 1999). The administration of haloperidol also impairs performance on a learning-dependent time estimation task (Zirnheld et al., 2004). Humans with damaged dopamine systems have impaired performance on time perception tasks (Pastor, Artieda, Jahanshahi, & Obeso, 1992; Pastor & Artieda, 1996). Individuals with Parkinson's disease show a pattern of responding that violates the scalar property when tested while off their medication, a hallmark of 'normal' temporal processing (Gibbon, 1977; Malapani et al., 1998). The pattern of deficits is consistent with a slowed internal clock (Pastor et al., 1992).

Arousal and Time Estimation

The relation between physiological arousal level and subjective time estimation has been posited by several researchers. Hoagland (1934) proposed an internal chemical-clock hypothesis that states that a relation exists between time estimation and body temperature, which can be described by the Arrhenius equation. According to this equation, for many common chemical reactions, the rate of the reaction increases two-fold for every 10° C increase in temperature. Hoagland conjectured that the pacemaker for subjective time is the speed of cellular metabolism, and because a rise in arousal level should result in a higher cellular metabolic rate, increased arousal will increase the subjective time rate (Cahoon, 1969).

In a review of the literature on body temperature and the rate of subjective time, Wearden and Penton-Voak (1995) found that that rate of subjective time increased when body temperature increased in almost all cases. Although rare, studies of decreased body temperature were associated with decreases in the rate of subjective time. The authors suggested that the most likely mechanism for the effects were the changes in arousal that resulted from the temperature manipulations. The results were consistent with a growing body of literature that supports the idea that humans and animals possess a timing mechanism that is sensitive to arousal.

Arousal levels have been linked to alpha electroencephalographic (EEG) activity, with high arousal being accompanied by a high frequency desynchronized EEG (low alpha index). Participants with a high alpha index have been shown to underestimate time when compared to participants with a low alpha index (i.e. high arousal, Werboff, 1957). In a study of dominant alpha activity, induced arousal, and subjective time estimation, no differences were found in subjective time estimation when arousal was induced through the threat of electric shock. However, there was a relation between chronic arousal levels as measured by the dominant alpha frequency and time estimation. The author interpreted this finding as support for the internal chemical-clock hypothesis.

Whereas several studies have been performed to examine the influence of stimulants such as nicotine, cocaine, and methamphetamines on timing, relatively few studies have examined the effects of caffeine administration. No studies could be located that examined the effects of caffeine administration on scalar timing tasks. However, caffeine administration has been shown to alter temporal estimates of longer durations, leading participants to underestimate time intervals when tested in the prospective paradigm (Gruber & Block, 2003). Low daily consumption of caffeine has been shown to improve the accuracy of time estimations in humans

(Stine, O'Connor, Yatko, Grunberg, & Klein, 2002). Sex differences in time estimations resulting from caffeine have been reported. Women who drank 300 mg of caffeine made shorter reproductions of a 10 second interval than women who drank a placebo. The same dose of caffeine did not alter men's reproductions (Botella, Bosch, Romero, & Parra, 2001).

A theoretical model had been proposed to explain the physiological and psychological effects of arousal agents such as caffeine (Smith, Tola, & Mann, 1999). According to this model, the relation between arousal input and output (e.g. blood pressure, behavior) describes an inverted U-shaped function. The effects of arousal agents are additive, such that higher arousal levels result from exposure to multiple agents than exposure to any one agent. Additive effects are also subject to the inverted-U principle. Furthermore, individual differences exist in susceptibility to arousal or arousability, which interact with exposure intensity to affect physiology and behavior. The effects of acute exposure to an arousal agent are diminished by habitual exposure.

The predicted additive effects of caffeine and other arousal agents have been demonstrated in blood pressure and electrodermal data. Stress and caffeine have additive effects on blood pressure and other cardiovascular indicators. In one study, participants given caffeine or a placebo were subjected to stress-inducing mental arithmetic, cold pressor, and static exercise tasks. Caffeine enhanced the impact of the stressors, eliciting an additive effect on blood pressure (France, & Ditto, 1992). In another study (Smith, 1994), participants who had been administered caffeine or a placebo received harassment while performing a stressful task. Caffeine without harassment produced an increase in blood pressure, while caffeine with harassment produced a decrease. This result is consistent with the inverted-U principle that the combination of caffeine and stress pushed the participants past the peak of the function and decreased arousal output.

Similar results have been obtained in electrodermal studies, in which the combination of caffeine and stimulus novelty yielded higher skin conductance levels and the addition of another stressor such as white noise reduces arousal output (Davidson & Smith, 1989; Smith et al., 1991).

The interactive effects of combining the arousal inducing acute exercise and caffeine are relatively unknown. The few studies on the effects of exercise and caffeine on cognition examined whether caffeine attenuates the negative impact of fatiguing exercise. For instance, a low dose of caffeine (150 g/l) was shown to improve attentional, psychomotor, and memory performance after an exhausting bout of exercise (Hogervorst et al., 1999). In a study by the same lead author, caffeine was shown to improve Stroop and information processing performance while performing a 2.5 hour exercise bout followed by an exhaustive time trial (Horgervorst et al., 2008). Even less understood is the effect of caffeine administration on cognitive performance during acute, steady-state exercise.

Therefore, the influence of caffeine administration on scalar timing is not known, nor is the effect of combining two arousal agents (such as caffeine and acute exercise) on interval timing. Combining the arousing effects of acute, aerobic exercise and psychostimulant drugs could result in different patterns of cognitive performance. For instance, if an interaction were observed between caffeine and the stages of information processing during exercise, it would indicate that both arousing agents had the same locus of influence on the flow of information processing. This would suggest a common energetic mechanism. In contrast, an additive pattern would indicate that both agents had an independent effect on the different stages of information processing, suggesting different energetic mechanisms (Audiffren, 2009).

Summary

Experimental time research has a long history. The scalar timing model, which describes the process by which intervals are timed and decisions are made based on timing information, is a viable model to explore how arousal manipulations influence timing behavior. There is evidence within the time estimation literature for a relation between arousal and the internal clock. The experimental portion of this dissertation was designed to examine scalar timing in humans during acute exercise, and to determine if the effects are isolated to changes in internal clock speed. Furthermore, the combined effects of two arousal manipulations (caffeine administration and acute exercise) were examined.

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CHAPTER 3

THE EFFECT OF EXERCISE-INDUCED AROUSAL ON COGNITION: A META-

REGRESSION ANALYSIS¹

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Abstract

The effects of acute exercise on cognitive performance were examined using metaanalytic techniques. The overall mean effect size was dependent on the timing of cognitive assessment. During exercise, cognitive task performance was impaired by a mean effect of -0.14. However, impairments were only observed during the first 20 min of exercise. Otherwise, exercise-induced arousal enhanced performance on tasks that involved rapid decisions and automatized behaviors. Following exercise, cognitive task performance improved by a mean effect of 0.20. Arousal continued to facilitate speeded mental processes and also enhanced memory storage and retrieval. Positive effects were observed following exercise regardless of whether the study protocol was designed to measure the effects of steady-state exercise, fatiguing exercise, or the inverted-U hypothesis. Finally, cognitive performance was affected differentially by exercise mode. Cycling was associated with enhanced performance during and after exercise, whereas treadmill running led to impaired performance during exercise and a small improvement in performance following exercise. These results are indicative of the complex relation between exercise and cognition. Cognitive performance may be enhanced or impaired depending on when it is measured, the type of cognitive task selected, and the type of exercise performed.

Key words: arousal; information processing; memory; executive function; fatigue

Introduction

Individuals often describe changes in their ability to perform mental tasks during and after exercise. For some, exercise leads to reports of increased mental acuity and clarity of thought. Others report feelings of mental disorientation and difficulty making decisions following exercise. The relation between individual bouts of exercise and cognitive function has been examined in more than 150 empirical studies over the past 50 years and the results summarized in several narrative reviews (Brisswalter, Collardeau, & Arcelin, 2002; McMorris & Graydon, 2000; Tomporowski, 2003; Tomporowski & Ellis, 1986). Only one quantitative review of the acute exercise literature has been published (Etnier, Salazar, Landers, Petruzzello, Han, & Nowell, 1997); which provided tentative support for a causal relation between exercise and cognitive function. A number of studies have been conducted in the past decade that provide a larger database from which theory-based hypotheses concerning the effects of exercise on brain and cognitive function can be evaluated.

Much of the research on the relation between exercise and cognition has tested predictions drawn from "arousal" theories (e.g., Yerkes-Dodson, 1908; Kahneman, 1973; Humphreys & Revelle, 1984; Sanders, 1986; Hockey, Gaillard, & Coles, 1986). Common to these theories is the assumption that cognitive performance is dependent on the allocation of energetical resources to meet task demands. Acute exercise has been hypothesized to alter brain systems that influence how mental resources are dedicated to cognitive task performance (Audiffren, 2009). While the evaluation of exercise-induced arousal has been at the center of the majority of published studies, the methods used to manipulate participants' arousal levels have not been uniform. Three different approaches have been taken to test predictions drawn from the arousal hypothesis. One approach has been to use experimental protocols that mimic the exercise

regimens prescribed to recreational runners or cyclists. These protocols involve steady-state cardiorespiratory exercise designed to improve mood and increase feelings of well-being. The aerobic-running movement that emerged in the 1970s was grounded on purported physical and psychological health benefits of steady-state exercise (Folkins & Sime, 1981). The existence of these benefits has been supported by empirical evidence, in which individuals report positive changes in affect following moderate levels of steady-state exercise lasting at least 20 min. Predictions for experiments that have examined cognition following exercise have been driven by this finding. Maintenance of exercise-induced arousal was expected for a short period following exercise and cognitive performance was also expected to be facilitated during this time.

A second approach researchers have taken to examine the exercise-cognition relation has been to model experimental protocols on predictions generated from the inverted-U hypothesis (Yerkes & Dodson, 1908) and other arousal theories (e.g. Humphreys & Revelle, 1984). Typically, cognitive performance was measured at multiple points during exercise that systemically altered participants' level of physiological arousal as measured by heart rate, oxygen uptake, RPE, or other biological indices. Cognitive performance was predicted to improve and peak as physiological arousal increased and then deteriorate as arousal levels approached maximal levels (see McMorris & Graydon, 2000).

Yet another approach to examine the influence of exercise on cognition has been to focus on the fatigue producing aspects of physical activity. Human factor researchers have long had an interest on the debilitating effects of physical fatigue on operational performance and exercise has been used to induce fatigue in many studies. Experimental protocols employed in these studies typically require participants to complete incremental-load exercise to voluntary

exhaustion or to maintain a physically demanding steady-state exercise protocol for an extended period of time. In such studies, it has been predicted that participants' cognitive performance would be impaired both during and immediately following the termination of exercise.

Thus, depending on the approach taken, researchers have expected exercise to either facilitate or impair cognitive function. Compounding attempts to elucidate the relation between exercise and cognitive function have been the wide range of mental tasks that have been employed in these studies. Tasks range from those that measure basic processes such as perceptual organization, information-processing speed, and simple- and choice-response time, to tasks that measure memory and high-level executive control processes. The different approaches taken by researchers, coupled with the wide variation in outcome measures, have made efforts to summarize and synthesize research findings difficult. Several authors have reviewed the results of these studies in a narrative fashion. In an early review, Tomporowski and Ellis (1986) classified studies according to the intensity and duration of the acute exercise intervention. The authors concluded that the empirical evidence did not provide support for the notion that exercise influenced cognition. They pointed to individual difference factors as a potential explanation, as well as a lack of a cohesive theory driving the research. In a later review, Tomporowski (2003) classified studies based on the intensity and duration of exercise and interpreted the results in terms of information-processing theory. Based on the available evidence, it was concluded that acute exercise had selective effects on cognitive processing. Exercise appeared to facilitate certain aspects of processing such as response speed and accuracy and enhanced the processes involved in problem-solving and goal-oriented actions. This was particularly true when a task involved inhibition of a response, one component of executive function. In contrast, exercise

appeared to have no effect on tasks that measured perceptual processing, sensory processing, or memory retrieval.

Other narrative reviews have targeted studies that employed specific exercise protocols. McMorris and Graydon (2000), for example, evaluated only those studies that were designed to test hypotheses derived from the inverted-U relation (Yerkes & Dodson, 1908). As mentioned, these researchers have predicted that cognitive test performance would rise to an optimal level as exercise-induced arousal increased and then decline with higher levels of physiological arousal. A similar approach to selecting research studies for evaluation was taken by Brisswalter et al. (2002). The conclusion drawn from these two narrative reviews was that certain aspects of cognitive performance improved during and after acute exercise. All three of these narrative reviews echoed a similar overall theme -- the results of studies were "equivocal."

Meta-analytic procedures provide an alternative method to examine the impact of acute exercise on cognition in terms of the magnitude and direction of its effect. While narrative reviews of acute exercise are informative, they do not permit a detailed examination of methodological differences that exist among studies and how these differences influence the size of the overall effect. To estimate the overall effect, individual effect sizes are calculated for the relevant studies and are aggregated in a systematic manner. An effect size is a statistic that captures the vital quantitative information from each relevant study finding. Effect sizes are standardized such that the values from different studies can be interpreted in a consistent way (Lipsey & Wilson, 2001, pp. 3-4). Meta-analytic procedures also permit examination of study and sample characteristics that moderate the size of the effect. An advantage of meta-analytic techniques compared to traditional narrative reviews is that the results are independent of

probability values and levels of statistical significance, which are largely dependent on sample size (Lipsey & Wilson, 2001, p.6).

Meta-analytic methods have been used to examine the relation between acute bouts of exercise and cognition. Etnier et al. (1997) derived 852 effects from 134 studies that examined the influence of both acute bouts of exercise and chronic exercise training on cognitive functioning. Of these effects, 371 represented the impact of acute exercise on cognition. The authors found that acute exercise had an overall small but significant positive (ES = 0.16) effect on cognition. Several moderator variables affected the magnitude of effect sizes, and those most relevant to the present work include: the type of cognitive task, the sampling method, and the number of threats to internal validity. Post-hoc analyses were performed to evaluate the role of cognitive task type and revealed larger effects for studies that used measures of simple reaction time than studies using choice- or discriminant-reaction time tasks. Study effect sizes were found to increase as the rigor of the experimental methods decreased, suggesting that poorly designed studies yielded larger effects.

However, interpretation of the analyses conducted by Etnier et al. (1997) is limited by several methodological factors. First, effect sizes were derived from different study designs (correlational, between-subject, within-subject, etc.) and combined for analysis. The merits of limiting meta-analytic procedures to effects sizes derived from comparable research designs have been described (Lipsey & Wilson, 2001 p. 45). Second, methods to adjust for the sample sizes of the studies were not employed. Weighting each effect based on sample size is important because larger studies provide more reliable parameter estimates of experimental effects than do studies with fewer participants. Each study's contribution to the meta-analysis should be proportionate to its reliability (Lipsey & Wilson, 2001, p. 106). Third, the analysis was limited to a fixed-

effects model, which considers only within-study variability. Contemporary researchers suggest that a random-effects model is preferable to a fixed-effect model because it accounts for between-studies heterogeneity. This heterogeneity is associated with the sampling error within studies as well as the shared random effects variance (Lipsey & Wilson, 2001, pp. 124-125, 140-142, 216-220).

The wide differences that exist in exercise interventions, populations studied, and types of cognitive tasks employed by researchers in this area warrant the use of a random effects model to aggregate the studies. This method may provide a more sensitive analytic approach than the methods used in previous studies. The present review focused exclusively on acute-exercise studies in which young adults' cognition was measured during or after single bouts of exercise using a within-subjects, repeated-measures design. The dual-task conditions of research protocols used to measure cognition during exercise (e.g., concurrent running and cognitive testing) differ theoretically from single-task protocols used to measure cognition following exercise (e.g., cognitive test only). Given these fundamental differences in attentional demands, studies that measured cognitive function during exercise were analyzed separately from those that measured cognitive function following exercise.

Selection of potentially moderating variables was guided by previous narrative and quantitative reviews and by contemporary cognitive theories. First, the relation between acute exercise and cognition was expected to be dependent on the exercise intensity and duration requirements placed on participants. As described previously, researchers have employed exercise protocols designed with a priori assumptions that interventions would either facilitate or degrade cognitive test performance. Second, the time at which cognitive tests were administered was expected to influence effect size, with larger effects expected during exercise as the length

of the exercise bout increased and the effects dissipating gradually following termination of exercise. The third hypothesis focused on exercise mode. Ergometer cycling and treadmill running exercise protocols have been used most frequently but relatively little distinction has been made between the two modalities. However, the attentional demands required to maintain a desired treadmill running pace might be greater than the demands when seated on a cycle ergometer. As such, fewer attentional resources would be available to runners to perform cognitive tasks than cyclists under dual-task conditions. Effect sizes were predicted to be smaller during exercise in studies that utilized running protocols when compared to effect sizes obtained from studies utilizing ergometer cycling protocols. The fourth hypothesis tested the supposition that acute exercise has selective effects on cognitive test performance. Effect sizes were predicted to be larger for tasks that emphasize processing speed, decision-making, and executive processing and smaller for tasks that involve memory encoding and retrieval processes. The final hypothesis addressed study-design factors. Studies with greater experimental rigor typically result in smaller effect sizes than studies with fewer controls. Thus, studies in which a resting control condition was included in the design were hypothesized to exhibit smaller effect sizes than studies that employed a pre- and post-exercise measurement design.

Methods

Literature search. Acute exercise studies that used an outcome measure involving cognition were located from searches of computer databases (Academic Search Premier, Medline, PsychINFO, Springerlink, Web of Science, PubMed) from 1900 to December 2008. Key words used in searches included "*acute exercise*", "*cognition*", "*executive function*", "*executive function*", "*executive processes*", "*reaction time*", "*attention*", "*vigilance*", "*decision-making*", "*detection*",

"memory", and *"perception."* These searches were supplemented by examining reference lists of previous reviews and meta-analyses.

Studies were included if they met the following criteria: the study was performed on healthy adults; the exercise intervention elicited the activation of large muscles and cardiovascular responses (e.g. studies that employed isometric muscle contractions or weightlifting were excluded); a repeated-measures, within-subject design was used; and the study was published in the English language. In studies where other independent variables were examined (e.g. administration of a pharmacological agent), control or placebo conditions in which the effects of exercise on cognition were assessed were also included when possible.

The literature search resulted in the location of 169 studies. Progression of the studies through exclusion stages is diagrammed in Figure 1. A total of 21 studies met criteria to be included in the analysis of studies with measures of cognition before exercise and during exercise, and 29 studies were included in the analysis of studies with pre-exercise and post-exercise cognitive measures. Ten studies were included in both analyses.

Study characteristics. The 21 studies that provided cognitive measures prior to and during exercise included a total of 292 participants. The studies had a median sample size of 14 participants (range = 8 - 41). One hundred and twenty-six effects were derived from these studies. The mean age of the samples was averaged; the grand mean was 22.9 years. Of the 21 studies included, 2 (9.5%) did not report the sex of the participants, 14 (66.7%) used a sample of males, 1 (4.8%) used a sample of females, and 4 (19.0%) used a sample that included both males and females.

Twenty-nine studies that included a total of 545 participants were included in the analysis of studies that provided pre- and post-exercise cognitive measures. The studies had a median

sample size of 15 participants (range = 6-100). A total of 109 effects were derived from these studies. The mean age of the samples were averaged; the grand mean was 23 years. Of the 29 studies included, 3 (10.3%) did not report the sex of the participants, 16 (55.2%) used a sample of males, 2 (6.9%) used a sample of females, and 9 (31.0%) used a sample that included both males and females. See Tables 1 and 2 for other characteristics of the studies used in the analyses.

Effect Size Calculation. Effect sizes for the single group, pretest-posttest designs were calculated using Cohen's *d* (Cohen, 1988; posttest minus pretest divided by the pretest standard deviation). For cross-over designs with a control condition, *g* (Hedges & Olkin, 1985) was calculated by subtracting the mean change for a control condition from the mean change for the experimental condition and dividing the difference by the pooled standard deviation of pretest scores (Hedges & Olkin, 1985). Effect sizes were adjusted for small sample bias using the correction factor: c = 1 - [3/4m - 9], where m = n - 1 (Hedges & Olkin, 1985). Effect sizes were calculated so that improvements in cognition resulted in positive effect sizes. When data were reported separately for men and women, the effects were averaged into one (Gleser & Olkin, 1994). Transformations from *t*-test values were not performed because transformations to *g* are based on sampling distributions of independent groups. If data were not provided in tabular format but were available in figures, means and standard deviations were estimated from the figures.

Statistical Analyses. A macro developed by Lipsey and Wilson (2001, pp. 208-121) was used with SPSS software (version 16.0) to calculate the aggregated mean effect size delta, the 95% confidence interval, and the sampling error variance using a random effects model. Effects were weighted by the degrees of freedom for within-subjects analysis (df: n - 1) and were then

re-estimated after the random effects variance component was added (Hedges & Olkin, 1985). Heterogeneity was indicated if Q_T was statistically significant ($p \le 0.05$) and the sampling error accounted for less than 75% of the observed variance (Hedges & Olkin, pp. 191-200). The weighted fail-safe sample size was computed to estimate the hypothetical number of unpublished or unretrievable studies of null effect and the mean weight necessary to overturn the significance of the mean effect to 0.05 (N+; Rosenberg, 2005).

Moderator variables and their levels were selected a priori based on logical, theoretical, and previous empirical relation between acute exercise and cognition. The primary moderator variables included the level of exercise demand, the timing of the cognitive measures, the exercise mode, the type of cognitive task, and the study design. All moderator variables were analyzed using a weighted least squares multiple linear regression to determine their independent contribution to the variation in effect size (Hedges & Olkin, 1985, pp. 167-188). This was done with a macro (SPSS, version 16.0) using a mixed effects model (Lipsey & Wilson, 2001, pp. 216-220). Moderators were coded in terms of planned contrasts between levels, with the provision that the number of effects (k) per level was 5 or greater. The effects were weighted by the within-subjects degrees of freedom. The number of effects per study was included in the regression model to determine potential bias resulting from non-independence of multiple effects from single studies (Gleser & Olkin, 1994). A debate remains about whether multiple effects should be averaged into a single effect or whether multiple effects should be included. The latter option was selected because including multiple effects from one study allows for exploration of moderators when the total number of studies available is small. Two-way interactions with the other moderators were added to the model when a significant main effect was found. Effect sizes

(95% CI), *p* values, sampling error, and contrast weights of levels within the moderators for cognitive effects are reported in Tables 3 and 4.

Results

Studies with Cognitive Measures During Exercise. Acute exercise led to an impairment of cognitive task performance, $\Delta = -0.14$ (95% CI = -0.26 to -0.01, p = 0.04). The mean effect size was statistically significant and heterogeneous (Q_T (125) = 807.09, p < 0.001). The fail-safe N+ (0.05) revealed that it would require two additional studies with null effects to overturn the significant result, indicative of publication bias in the literature contributing to this overall mean effect. The distribution of 126 effects was negatively skewed ($g_1 = -1.12 \pm 0.22$) and leptokurtic ($g_2 = 1.52 \pm 0.43$). Forty-eight percent (N = 58) of the effects were less than zero.

The overall multiple regression model including all moderators was statistically significant (Q_R (6) = 58.95, p < 0.001, $R^2 = 0.32$). After accounting for the moderator variables, the random effects variance component was estimated (Q_E (119) = 125.26, p = 0.33). Three of the primary moderators were independently related to the size of the effect. Effect size was dependent on when the cognitive tasks were administered relative to the onset of exercise ($\beta = 0.30$, z = 3.75, p < 0.001), with negative effect sizes occurring during the first 20 min of exercise and positive effects occurring when measured after the first 20 min (see Figure 2). Effect size was also dependent on exercise mode ($\beta = 0.33$, z = 4.23, p < 0.001). The effect sizes were larger in studies that involved a running or treadmill modality when compared to studies with cycling exercise. It should be noted that the effect size for the studies that used treadmill exercise was negative, whereas, the effect size for studies that used cycling exercise was positive (see Figure 3). Finally, effect sizes were dependent on the type of task used ($\beta = 0.26$, z = 3.37, p < 0.001),

with positive effects for tasks that measured "inspection time" (e.g. visual search) and negative effects for perceptual tasks (e.g. line matching) and tasks that measured processing speed (e.g. response/reaction time). The number of effects per study was significant ($\beta = -0.29$, z = -3.64, p < 0.001), indicating that the inclusion of multiple effects per study was a source of bias in the analysis.

A second model that added the two-way interactions among the significant moderators was significant ($Q_R(12) = 78.15$, p < 0.001, $R^2 = 0.38$; $Q_E(113) = 124.95$, p = 0.21). Two significant interactions emerged when potential interactions between significant moderators were added to the regression model. The design × timing of cognitive measurement interaction was significant ($\beta = -0.20$, z = -1.98, p = 0.04). Studies without a control group had larger negative effects when cognitive testing was performed during the first 20 min of exercise when compared to controlled studies, and larger positive effects when cognitive testing was performed after 20 min of exercise. The task type × exercise demand interaction was also significant ($\beta = -0.82$, z = -2.29, p = 0.02), indicating that the effects from processing speed tasks were positive during steady state exercise but negative when the exercise demand was designed to evaluate the effects of fatigue or the inverted-U hypothesis (see Figure 4).

Studies with Cognitive Measures Following Exercise. Acute exercise led to a small improvement in cognitive task performance following the exercise bout, Δ = 0.20 (95% CI = 0.14 to 0.25, *p* < 0.001). The mean effect size was statistically significant and heterogeneous (*Q*_T (108) = 134.89, *p* < 0.04). The fail-safe *N*+ (0.05) revealed that it would require 1,625 additional studies reporting null effects to overturn the significant result. The distribution of 109 effects was positively skewed (*g*1 = 0.73 ± 0.23) and leptokurtic (*g*2 = 1.22 ± 0.46). Twenty-one percent (N = 23) of the effects were less than zero.
The overall multiple regression model including all moderators was statistically

significant ($Q_R(6) = 27.52$, p < 0.001, $R^2 = 0.21$). After accounting for the moderator variables, the random effects variance component was estimated ($Q_E(102) = 103.28$, p = 0.45). Three of the primary moderators were independently related to the size of the effect. Effect sizes were dependent on exercise mode ($\beta = 0.21$, z = 2.02, p = 0.04) with smaller effect sizes from studies that involved a running or treadmill modality than studies in which cycling exercise was used (see Figure 3). Effect sizes were also dependent on the type of task used ($\beta = 0.32$, z = 3.15, p =0.002), where smaller effects were observed for tasks that measured processing than tasks that measured memory. Finally, effect size was dependent on the study design ($\beta = 0.32$, z = 2.90, p =0.004); effect sizes were larger in studies that did not include a control condition than those that did. The number of effects per study was significant ($\beta = 0.22$, z = 2.12, p = 0.03), indicating that the inclusion of multiple effects per study was a source of bias. A second model that added the two-way interactions among the significant moderators was significant ($Q_R(15) = 38.25$, p <0.001, $R^2 = 0.28$; $Q_E(93) = 96.63$, p = 0.38), but none of the interactions was statistically significant.

Discussion

The impact of acute exercise on cognitive task performance was evaluated via metaanalytic techniques. Effect sizes were derived from studies that measured cognitive function before, during, and after exercise. Similar to the meta-analysis performed by Etnier et al. (1997), acute exercise significantly altered young adults' cognitive test performance and the magnitude of the effect was small (Cohen, 1988). The direction of the effect depended on when cognitive performance was assessed. The overall effect size indicated that participants' cognitive performance was impaired during exercise, Δ = -0.14, whereas following exercise there was an improvement in cognitive task performance, Δ = 0.20. The interpretation of each of these analyses must be qualified, however, as several moderators in each analysis were independently related to overall effect size.

Cognitive test performance during exercise. Analysis of studies that examined the impact of exercise on cognition during physical activity revealed several significant moderator variables. First, different results were yielded based on the point in time that participants performed cognitive tests. Averaging the effect sizes according to the time interval between exercise onset and cognitive test performance revealed that participants' performance declined during the initial 10 min of exercise and subsequent 10 min interval. However, performance was facilitated when cognitive testing occurred after 20 min of exercise or longer (see Figure 2 and Table 3).

Exercise physiologists have assessed how specific areas of the brain are involved in the initiation of physical activity and how feedback from the body determines the point at which physical activity is reduced or stopped (Williamson, 2006; Kayser, 2003). Participants in exercise studies are asked to pedal or run voluntarily for specified durations. A multitude of changes begin to occur within the body as neurological signals to begin exercise are sent from the motor cortex of the brain. Within seconds, metabolic energy pathways are made available to provide peripheral and central systems with the resources required to meet the physical demand (Secher, Siefert, Nielsen, & Quistorff, 2009). During the initial phase of exercise, sensory feedback from numerous peripheral systems is routed through the thalamus and other diencephalon structures to striatal and prefrontal lobe circuits, which then provide top-down regulation of motor commands. Many of the neural processes that adjust motor commands occur without awareness; however, other adjustments (e.g., physical interactions with cycle ergometers)

or motorized treadmills; orientation with equipment used for cognitive testing; instructions or feedback from laboratory personnel) require participants' attention.

The changes that occur in the brain during the initiation and maintenance of exercise have been linked to shifts in cognitive performance. Classic and contemporary theories of attention assume that attention has a limited capacity, which can compromise cognitive performance when there is a competition for resources (e.g., Kahneman, 1973; Hockey, 1997). Dual-task interference may provide a viable explanation for the negative effects sizes observed during the first few minutes of acute exercise. Researchers (Audiffren, 2009; Dietrich, 2009; Pesce, 2009) have discussed the role of dual-task demands on attentional allocation during acute exercise. According to the hypofrontality hypothesis proposed by Dietrich (2003), the neural circuitry involved in the initiation, control, and maintenance of motor movements requires considerable metabolic resources. As a consequence, available resources are drawn from cortical networks that control less immediately critical behaviors, such as pre-frontal lobe networks. Similar to the conceptual single-pool attentional resources theories proposed by Dietrich (2003) predicts declines in complex mental processing during periods of physical activity.

Some exercise protocols employed in the studies reviewed involved a relatively brief "warm up" period of 3 to 5 min, which was followed by increases in exercise demand. Participants exercised until they reached a designated level to ensure that an aerobic steady-state exercise bout could be maintained (e.g., Audiffren, Tomporowski, & Zagrodnik, 2008). In other studies, the physical demand increased incrementally or gradually throughout the exercise session and was maintained at levels that required participants to draw upon anaerobic energy sources (e.g., Bender & McGlynn, 1976). Moderator analysis revealed that participants'

cognitive performance improved over pre-exercise levels when tested after 20 min of exercise. However, exercise type interacted with the type of cognitive task performed. Performance on information-processing tasks (e.g., simple, choice, and discriminant response time) improved during steady-state aerobic-type exercise but was negatively impacted during physically challenging and primarily anaerobic exercise (see Figure 4).

Improvements in information processing during steady-state, dynamic whole-body exercise have been predicted by several investigators (Davranche & Audiffren, 2004; Tomporowski, 2003) who suggest that these improvements are driven by alterations in brain neurotransmitter systems. McMorris (2009) proposed a neuroendocrinological model to predict exercise conditions that would either facilitate or hinder cognitive function. With the onset of physical activity, the hypothalamus triggers the synthesis of catecholamines in the sympatheticadrenal-system axis. As exercise increases in intensity, adrenaline and noradrenaline are released from the adrenal medulla, signaling the release of catecholamines in the brain. Norepinephrine and dopamine, in particular, are thought to influence the brain networks responsible for information processing. Moderate increases in the level of these two neuromodulators could influence pre-frontal lobe attentional systems by altering background neural noise relative to target saliency (Masulam, 1990). An enhanced signal-to-noise ratio may improve stimulus encoding, decisional processes, and response mobilization, and explain the reductions in exercisers' response times during steady-state aerobic exercise.

McMorris' (2009) model also provides a viable explanation for the negative effect sizes observed when cognitive performance was measured during protocols designed to test the inverted-U hypothesis. While acute exercise leads to the increased peripheral levels of adrenaline and noradrenaline, there are also neuroendocrine responses initiated by the hypothalamic-

pituitary system axis. The release of cortisol is thought to modulate arousal by limiting the synthesis of corticotrophin releasing hormone (CRH) and adrenocorticotrophin hormone (ACTH). As exercise increases in intensity or duration, cortisol production is unable to inhibit CRH and ACTH and arousal levels increase to the point that cognitive performance is compromised. Alternatively, alterations in exercise demands and the behavioral adjustments required of participants may have resulted in dual-task conditions during which exercisers' attention was allocated to the control of running or cycling rather than the performance of cognitive tasks.

Partial support for the dual-task attentional allocation explanation is provided by the second significant moderating variable, exercise mode. As depicted in Figure 3 and described in Table 1, there were clear differences between participants' cognitive performance when running as opposed to ergometer cycling. Pesce (2009) articulated the need to be cognizant of the skill level and sport experience of participants in acute exercise studies. Laboratory motorized treadmill protocols are well suited to obtain physiological data; however, they constitute rather novel experiences for even highly trained athletes. Compared to cycle ergometer riding, treadmill running requires considerably more balance and upper and lower-body coordination. While not studied directly, failure to maintain a sufficient running pace on a treadmill is probably more disruptive to runners' attention because losing balance increases the risk of falling. In contrast, cyclists can simply modify their cycling cadence. Future research may help clarify the acute exercise-cognition relation by examining the role of exercise modality and skill level of the participants.

The third significant moderator variable indicated that acute exercise influenced participants' performance on some cognitive tests more than others. As described above,

performance on tests that stressed information-processing speed and response speed were dependent on exercise demand. In addition, the weighted mean of the effects for tasks that measured inspection-time speed (e.g., visual search) was positive and differed significantly from the mean of the effects for tasks that required participants to make choice responses on the basis near-threshold perceptual discrimination (e.g., line matching) and response time tasks. Neurophysiological arousal during exercise may have its greatest impact on basic bottom-up processes and automatic processing, and have minimal or no effect on higher-level, top-down processes.

Cognitive test performance following exercise. Regardless of the type of physical activity performed, participants' cognitive performance improved when tested after exercise. The findings regarding steady-state exercise confirm predictions made by several researchers that metabolic recovery occurs gradually and the heightened level of arousal during this period facilitates cognitive function (Tomporowski, 2003; Audiffren et al., 2008). Interestingly, participants' cognitive performance also improved following exercise protocols designed to induce physical fatigue. The anecdotal evidence for the debilitating effects of acute fatigue on attention and cognition and resultant decrease in performance is overwhelming; however, this phenomenon has been elusive in laboratory studies. Results from the studies that have focused on the relation between acute physical fatigue and operational performance have been inconsistent. These inconsistencies have been explained in terms of individual differences in participants' physical fitness, the intensity and/or duration of exercise, the nature of the psychological task, and the time at which the task is administered (Grego et al., 2004). The duration of exercise may be particularly important given that the few studies that report decrements in cognitive function have required participants to exercise for two hours or more

and have also manipulated hydration levels (Cian, Koulmannn, Barraud, Raphel, Jimenez, & Melin, 2000; Cian, Barraud, Melin, & Raphel, 2001; Grego et al., 2004; Tomporowski, Beasman, Ganio, & Cureton, 2007). This pattern of results suggest that typical laboratory-based exercise protocols that are presumed to produce fatigue may be insufficient to simulate the physiological demands encountered in naturalistic sport and extreme human performance environments. Alternatively, several of the studies that have reported decrements in cognitive function did not meet the inclusion criteria for this analysis and their findings did not contribute to the results.

It was also the case that a significant positive effect size was obtained from studies designed to test the inverted "U" hypothesis. In the majority of these studies, participants' cognitive performance was evaluated several times during a session. Bender and McGlynn (1976), for example, varied exercise intensity in stages that placed various levels of aerobic or anaerobic cardiorespiratory demands on participants. Cognitive tests were administered following each stage of exercise with the expectation that performance would be facilitated by low-to-moderate levels of aerobic exercise and debilitated by intense aerobic exercise. Together, the results of studies conducted to assess fatigue and studies designed to assess the inverted-U hypothesis suggest that young adults may be able to maintain cognitive efficiency following relatively brief periods of physically demanding exercise. Despite researchers' longstanding interest in understanding the construct of mental fatigue (Bartley & Chute, 1947; Holding, 1983), a laboratory model that reliably links physical fatigue to cognitive performance has yet to be developed.

Several moderators were independently related to the size of the overall effect. As shown in Figure 3 and Table 4, exercise mode was a significant moderator, with larger effect sizes

associated with ergometer cycling than with running protocols. While cycling and running are aerobic activities that utilize large muscle groups, differences in muscle recruitment patterns between these two activities invoke different aerobic and anaerobic contributions to exercise energy expenditure. Cycling requires less metabolic energy compared to running because the vertical excursion of the body's center of mass is reduced by maintaining a seated position. The cycling position allows muscles to contract in a more efficient range of movement than does running (Bijker, de Groot, & Hollander, 2002; Scott, Littlefield, Chason, Bunker, & Asselin, 2006). It is plausible that after running, sensory afferents continue to influence the integration of cortical activation and lower the signal-to-noise ratio, which results in less efficient information processing, discrimination, and detection. Support for a neural interference interpretation comes from three studies in which event-related potentials were measured to assess P3 waveforms following moderate or heavy exercise. The amplitude of the P3 wave increased and latency decreased after moderate exercise, which was indicative of improved decision-making processes (RPE 12-14: Kamijo et al., 2004; 50% VO_{2max}: Kamijo, Hayashi, Sakai, Yahiro, Tanaka, & Nishihira, 2009). However, no changes in P3 indices were observed following heavier exercise (RPE 15, Kamijo et al., 2006) and decreases in P3 amplitude as well as longer latencies were detected following cycling to exhaustion (Kamijo et al., 2004). Additional study of the shortterm after effects of exercise on the brain will be required to determine if and why cognitive performance is affected differentially by exercise mode. Little is known, for example, of the effects of circuit- and resistance-training exercise protocols on cognitive function.

The type of cognitive task performed following exercise also moderated the exercisecognition relation. The weighted mean of effects from studies that employed tests of memory was significantly larger than the weighted mean of effects from studies that measured executive

function or information-processing time. These results differ from predictions made in previous narrative reviews, which hypothesized that acute exercise would minimally affect memory encoding and retrieval processes (Tomporowski, 2003). The results of several recently conducted studies contribute to a better understanding of the exercise-cognition relation (Coles & Tomporowski, 2008; Tomporowski & Ganio, 2006).

The link between acute exercise and memory storage and retrieval processes has important practical and theoretical ramifications. Traditionally, exercise-induced arousal has been viewed as a factor that temporarily influences performance. Similar to the effects of stimulant drugs, once exercise-induce changes in the central nervous system dissipate, behavior is thought to return to baseline levels. Given that acute exercise can alter memory processes, it may also impact learning, which is a relatively permanent change in behavior. The link between acute exercise and memory processes may help explain why chronic exercise interventions, which are composed of a series of acute exercise bouts, favorably impact executive function and memory processes in older adults (Colcombe & Kramer, 2003) and children (Davis et al., 2007; Hillman, Castelli, & Buck, 2005). Experiences acquired over repeated bouts of physical activity may alter the manner in which individuals adapt to novel conditions that require goal-directed planned behaviors (Pesce, 2009).

This review revealed that the study design was a significant moderator in the regression analysis of studies that measured cognition following exercise. Similar to Etnier et al's metaanalysis (1997), smaller effects were observed in studies that included a control condition. Single-group designs with pre- and post- intervention measures are one of the weakest experimental designs because they do not control for extraneous factors such as practice effects and the passage of time (Campbell & Stanley, 1963). It requires extra time and resources to

include a resting control condition; nevertheless, it is necessary to prevent overestimation of the effects of acute exercise on cognitive task performance.

On the basis of arousal theory, it was predicted that the effect of an exercise bout on cognitive performance would decline with the lengthening of the interval between the termination of exercise and measurement of cognitive performance. The moderator analysis did not provide support for this hypothesis. Very few researchers have designed studies that systematically investigated how cognitive performance changes either during and/or following the termination exercise. The results from the studies that have closely examined time-related changes in cognitive performance suggest that the effects of exercise may be subtle and influenced by a variety of factors (e.g., Audiffren et al, 2008).

In the analyses of studies that measured cognition during exercise and studies that assessed cognitive performance following exercise, visual inspection of the effect sizes associated with different levels of descriptive variables revealed that effect sizes were similar across levels. No differences were noted among the weighted mean effects from studies using male-only samples, female-only samples, and mixed samples. However, it should be noted that females are underrepresented in this literature, particularly in studies with measures of cognition during exercise. Similarly, there were no visible differences in weighted mean effects for fitness levels that could be coded based on VO_{2max} scores (data not shown). Tests of VO_{2max} were administered and reported in only 38% of the studies assessing cognition during exercise and 41% of the studies measuring cognition following exercise. The failure to include indices of cardiorespiratory fitness may be particularly problematic for studies designed to assess fatigue effects. A high exercise workload may not produce the same pattern of fatigue in highly cardiovascular fit individuals as compared to those with lower levels of aerobic fitness. Exercise

studies that include a test of maximal aerobic capacity and utilize an exercise intensity that is relative to each participant's maximum may help resolve the inconsistencies found within the literature.

The studies selected in the present analysis were restricted to those that evaluated healthy adults between the ages of 18 and 30 and, as such, generalizations to other age groups and individuals with physical impairment or disease state are limited. The restricted criterion for selection was driven partly by the paucity of well-controlled studies conducted with middle-aged adults, and older adults. Only one study with older adults fit the inclusion criteria for this analysis (Molloy, Beerschoten, Borrie, Crilly, & Cape, 1988), but was ultimately excluded in the interest of a homogenous group of studies. More research is needed to assess how acute exercise affects the cognitive function of middle-age and older adults who are experiencing age-related changes in physical function. Also excluded from our analyses was the small number of studies that assessed the effects of acute bouts of exercise on childrens' and adolescents' cognitive function. The results of these studies have been summarized in narrative (Tomporowski, 2003; Tomporowski, Davis, & Miller, 2008) and quantitative reviews (Sibley & Etnier, 2003). These reviewers highlight a number of developmental and maturational factors that affect responses to exercise that may not play a role in the exercise-cognition relation in healthy young adults.

Similar to observations made by Etnier and her colleagues (Etnier et al., 1997; Chang, Etnier, & Barella, 2009; Etnier, Nowell, Landers, & Sibley, 2006), this review of the literature revealed that a wide number of cognitive tests have been used to assess the acute exercisecognition relation. The tests also vary considerably in their psychometric properties and reliability (see Tomporowski, 2009; Chang et al., 2009 for commentaries). As a result, it has been challenging for researchers to categorize tests according to the mental processes they

purportedly measure. The coding approach in this analysis was influenced by a cognitive-test classification system developed by Carroll (1993); however, it was used in a more restrictive fashion than in previous meta-analytic reviews (Etnier et al., 2006). The cognitive test categories that were established were also based on contemporary theoretical views of information-processing, executive function, and memory (see Miyake & Shah, 1999) and commentaries concerning coding practices and their impact on the results of meta-analytic studies (Angevaren, Aufdemkampe, Verhaar, Aleman, & Vanhees, 2008).

In summary, this quantitative synthesis of the literature supports earlier reviews, which concluded that acute bouts of exercise have an influence on cognitive function. The separate analysis of studies that measured cognitive performance during exercise and those which assessed cognition following exercise review adds to the literature in this area. The picture that has emerged from recent narrative and quantitative reviews of acute exercise indicates that the exercise-cognition relation is complex. Cognitive performance may be enhanced or impaired depending on when it is measured, the type of cognitive task selected, and the type of exercise performed. During exercise, arousal appears to impact basic bottom-up mental processes and enhance performance on tasks that involve rapid decisions and automatized behaviors. Following exercise, arousal continues to facilitate speeded mental process and also enhances memory storage and retrieval. Thus, under specific conditions exercise may prime individuals to perform simple tasks rapidly and efficiently and then retain information concerning the results of those actions. This speculation must be tempered, however, as only a few exercise studies have focused on memory processes. It is particularly important that more well-designed experiments are conducted that measure encoding and retrieval processes. The finding that learning is facilitated by individual bouts of exercise may be very helpful for researchers who strive to

explain how repeated individual bouts of exercise (i.e. chronic exercise programs) alter specific cognitive processes.

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Figure 3.1. Flow Diagram for Inclusion of Studies



Figure 3.2. Mean Effect Size as a Function of When Cognitive Task was Administered Relative to Exercise Onset



Figure 3.3. Mean Effect Size for Cognitive Measures During and After Exercise



Figure 3.4. Mean Effect Sizes for Processing Tasks Performed During Exercise as a Function of Exercise Demand

Author	N	Design	Sex	Exercise Mode	Exercise Duration	Exercise Demand	# of Effects	Task(s) Used	ES Range
^a Ando et al., 2005	9	C ^b	MA	Cycle	21 min	Fatigue	9	RT	-0.53 to 0.30
^a Audiffren et al., 2008	17	С	Mixed	Cycle	40 min	Steady-state	5	CRT	0.10 to 0.30
^a Bender & McGlynn, 1976	10	NC	MA	Running	12 min	Inverted-U	12	RT	-2.80 to -1.10
Brisswalter et al., 1995	10	NC	Males	Cycle	~57 min ^c	Inverted-U	6	RT	-2.32 to -0.32
^a Collardeau et al, 2001	11	NC	NR	Running	90 min	Fatigue	5	RT	-0.45 to 0.60
^a Collardeau et al, 2001	8	NC	NR	Running	100 min	Fatigue	2	RT, CRT	-0.58 to -0.46
Kruk et al., 2001	9	NC	MA	Cycle	to exhaustion	Fatigue	6	CRT	-1.89 to 0.27
McMorris & Graydon, 1997	12	NC	MA	Cycle	NR	Inverted-U	10	Visual search	-0.29 to 0.84
McMorris et al., 2003	9	NC	MA	Cycle	NR	Inverted-U	4	CRT	0.16 to 0.76
McMorris et al., 2005	9	NC	MA	Cycle	NR	Inverted-U	8	CRT	-0.15 to 0.80
McMorris et al., 2008	12	NC	MA	Cycle	6 min	Inverted-U	8	CRT, RNG	-0.46 to 0.52
^a McGlynn et al., 1977	14	NC	MA	Running	12 min	Inverted-U	8	Line matching	-0.64 to 0.57
^a McGlynn et al., 1979	15	NC	F	Running	12 min	Inverted-U	8	Line matching	-0.34 to 0.16
Pesce et al., 2003	16	NC	MI	Cycle	NR	Steady-state	2	Attention task	-0.91 to 1.43
Pontifex & Hillman, 2007	41	С	MI	Cycle	~12 min	Steady-state	1	Flanker task	-0.81
Reilly & Smith, 1986	10	NC	MA	Cycle	NR	Inverted-U	5	Pursuit rotor	-0.98 to 0.44

Table 3.1. Characteristics of Studies Used in the Analysis of Cognitive Function During Exercise

Serwah & Marino,									
2006	8	NC	MA	Cycle	~90 min	Fatigue	3	CRT	0.66 to 0.96
^a Sjoberg, 1977	25	NC	MA	Cycle	~52 min	Inverted-U	15	RT, CRT	-1.32 to 1.00
^a Vercruyssen et al.,								Time	
1989	11	NC	MA	Cycle	NR	Steady-state	1	estimation	0.73
^a Yagi et al., 1999	24	NC	MI	Cycle	10 min	Inverted-U	2	Oddball	0.15 to 0.49
Zeimba et al., 1999	15	NC	MA	Cycle	to exhaustion	Fatigue	6	CRT	-0.55 to 0.63

Note. C=controlled; NC=not controlled; MA=males; F=females; MI=mixed; NR=not reported; RT=response time; CRT=choice response time, DRT=discriminant response time, RNG=random number generation. ^astudies included in both analyses. ^b 3 effects from this study did not have a control and were computed using Cohen's d (Cohen, 1988). ^cnot including rest periods.

Author	N	Design	Sex	Exercise Mode	Exercise Duration	Exercise Demand	# of Effects	Task(s) Used	ES Range
Aks, 1998	16	NC	MI	Cycle	10 min	Inverted U	2	Visual search	0.14 to .023
Al-Nimer et al., 2007	14	NC	MI	Cycle	6 min	Steady state	4	CFF, CRT	-0.17 to 0.38
Ando et al., 2005	9	С	MA	Cycle	21 min	Fatigue	1	RT	0.04
Audiffren et al., 2008	17	С	MI	Cycle	40 min	Steady state	3	CRT Viewel accest	-0.27 to -0.18
Bard & Fleury, 1978	16	NC	MA	Cycle	16-19 min	Fatigue	6	Bassin timer	-0.01 to 0.39
1976	10	NC	MA	Running	12 min	Inverted U	3	RT ST, immediate and delaved	-0.16 to 0.13
Coles et al., 2008	18	С	MI	Cycle	40 min	Steady state	6	recall	-0.05 to 0.30
Collardeau et al, 2001	11	NC	NR	Running	90 min	Fatigue	1	RT	0.25
Collardeau et al, 2001	8	NC	NR	Running	100 min to	Fatigue	2	RT, CRT	-0.12 to 0.10
Cote et al, 1992	17	NC	MA	Cycle	exhaustion	Fatigue	2	RT	0.40 to 0.51
Crews, 1979	10	NC	MA	Running	3-30 min	Fatigue	3	RT	-0.47 to -0.06
Davranche & Pichon, 2005	7	NC	MA	Cycle	to exhaustion	Fatigue	2	CFF	0.33 to 0.49
Ferris et al., 2007	15	NC	MI	Cycle	30 min	Inverted U	9	Stroop Coincidence	0.10 to 0.60
Fleury et al., 1981	15	NC	NR	Cycle	45 min to	Steady state	2	task	0.37 to 0.39
Godefroy et al., 2002	6	NC	MA	Running	exhaustion	Fatigue	8	CFF	-0.17 to 0.78
Gondola, 1985 Hogervorst et al.	19	NC	MI	Running	20 min	Steady state	2	OC, AU Stroop, RT, CRT, DRT.	0.57 to 0.98
1996	15	NC	MA	Cycle	~60 min	Fatigue	7	finger tapping	0.12 to 0.37
Jette et al., 1988	100	NC	MA	Running	20 min	Fatigue	4	RT	-0.04 to 0.24

Table 3.2. Characteristics of Studies Used in the Analysis of Cognitive Function Following Exercise

Kashihara &									
Nakahara, 2005	14	С	MA	Cycle	10 min	Steady state	5	CRT	0.24 to 1.2
McGlynn et al., 1977	15	NC	MA	Running	12 min	Inverted U	2	Line matching	-0.42 to -0.08
McGlynn et al., 1979	15	NC	F	Running	12 min to	Inverted U	2	Line matching	0.16 to 0.46
Presland et al., 2005 Shanmugan &	15	NC	MA	Cycle	exhaustion	Fatigue	4	CFF CFF, spiral after, RT,	-0.05 to 0.26
Narayanan, 1973	20	NC	NR	Cycle	10-20 min	Fatigue	10	CRT, DRT	-0.07 to 1.07
Sjoberg, 1977	25	NC	MA	Cycle	~52 min	Inverted U	3	RT, CRT	0.02 to .50
Themanson & Hillman, 2006 Tomporowski et al	28	С	MI	Running	30 min	Steady state	1	Flanker	-0.15
2005 Tomporowski et al	19	NC	MI	Cycle	40-120 min	Steady state	2	PASAT Switch task	0.29 to 0.36
2006 Vercruyssen et al	22	С	MI	Cycle	40 min	Steady state	10	BP Time	0 to 0.36
1989	11	NC	MA	Cycle	NR	Steady state	1	estimation	.08
Yagi et al., 1999	24	NC	MI	Cycle	10 min	Steady state	2	RT	-0.18 to -0.13

Note. NC=not controlled, C=controlled, MA=males; MI=mixed, F=female, NR=not reported; RT=response time, CRT= choice response time; DRT=discriminant response time; CFF=critical flicker fusion; PASAT=paced auditory serial addition task; OC=obvious consequences; AU=alternate uses; ST=switch task; BP=Brown Peterson

	Contrast	Effects		95% CI	95% CI	
Effect modifier	weights	(k)	Δ	Low	High	p-value
Exercise Demand						
Steady State	1	9	0.16	-0.13	0.73	0.53
Fatigue	-1/2	31	0.05	-0.15	0.24	0.61
Inverted-U	-1/2	86	-0.23	-0.39	-0.07	0.01
Timing of Cognitive Tas	sk relative to	Exercise	Onset			
NR	0	48	0.09	-0.09	0.27	0.33
0-10 min	-1/2	49	-0.27	-0.46	-0.08	0.00
11-20 min	-1/2	20	-0.61	-1.05	-0.16	0.01
20+	1	9	0.39	0.15	0.63	0.00
Exercise Mode						
Running	-1	35	-0.57	-0.85	-0.28	0.00
Cycling	1	91	0.03	-0.10	0.16	0.69
Task Code						
Executive Function	0	5	0.03	-0.53	0.60	0.91
Perception	-1/2	9	-0.12	-0.39	0.15	0.38
Inspection time	1	14	0.18	-0.02	0.38	0.08
Processing Speed	-1/2	98	-0.19	-0.35	-0.04	0.08
Design						
Not Controlled	-1	114	-0.15	-0.29	-0.01	0.04
Controlled	1	12	-0.03	-0.30	0.24	0.82

Table 3.3. Cognitive Effect Sizes Measured During Exercise (95% CI), P-values, and Regression Contrast Weights for Levels of Effect Modifiers

	Contrast	Effects		95% CI	95% CI		
Effect modifier	weights	(k)	Δ	Low	High	p-value	
Exercise Demand							
Steady State	- 1/2	35	0.19	0.09	0.28	0.00	
Fatigue	1	51	0.21	0.13	0.29	0.00	
Inverted-U	- 1/2	23	0.18	0.07	0.28	0.00	
Timing of Cognitive Tas	sk relative to	Exercise	Cessat	tion			
NR/Other	0	30	0.36	0.25	0.47	0.00	
Within 15 min	1	62	0.12	0.07	0.18	0.00	
After 15 min	-1	17	0.06	-0.07	0.20	0.36	
Exercise Mode							
Running	-1	28	0.12	0.01	0.22	0.03	
Cycling	1	81	0.23	0.17	0.29	0.00	
Task Code							
Memory	1	9	0.30	0.06	0.55	0.01	
Processing	-1	87	0.18	0.12	0.24	0.00	
Executive Function	0	13	0.19	0.05	0.32	0.01	
Design							
Not Controlled	1	82	0.22	0.16	0.28	0.00	
Controlled	-1	27	0.13	0.03	0.22	0.01	

Table 3.4. Cognitive Effect Sizes Measured following Exercise (95% CI), p-values, and Regression Contrast Weights for Levels of Effect Modifiers

CHAPTER 3

EXPERIMENT 1: THE EFFECTS OF ACUTE EXERCISE ON TEMPORAL

GENERALIZATION

Lambourne, K. and Tomporowski, P.D. To be submitted to *Quarterly Journal of Experimental Psychology*.

Abstract

Objective: Temporal generalization is a technique used to examine timing behavior and the speed of the internal clock. There is evidence that the internal clock is sensitive to arousal, but the effects of exercise-induced arousal have not been studied. A within-subjects, repeated measures design was used to examine temporal generalization during exercise. Methods: Sixteen healthy college students performed temporal generalization tasks before and during moderate-intensity aerobic exercise. Exercise was performed on two separate occasions and a different temporal generalization task was administered during each session. For the multipletrial referenced task, the participant compared a series of durations to two fixed standards. For the episodic temporal generalization task, the participant compared the duration of two stimuli on each trial. The same tasks were administered in a resting control condition. A working memory task was also administered in close temporal proximity to the timing tasks to examine the locus of the effect of exercise within the scalar timing model. Results: Temporal generalization gradients demonstrated leftward shifts during exercise when compared to rest consistent with an increased pacemaker speed. Exercise did not prevent subjective lengthening of stimuli. No significant differences were observed on an episodic timing task, which relies more on working memory, nor were any differences found on the working memory tasks. This provides support for the role of the internal clock as the component of the scalar timing model that is influenced by exercise. Conclusions: exercise is a safe and viable way to alter the speed of the internal clock.

Key words: scalar timing, temporal discrimination, physical activity, working memory, cognition
Introduction

There has been longstanding interest in the subjective experience of time and the influence of time perception on behavior. Empirical investigation of time perception dates back to the pioneers of experimental psychology, and large bodies of literature have since accumulated that describe timing experiments with humans and animals. A subset of this literature is the timing of relatively short durations in the range of seconds to minutes. These intervals are crucial because they unite mental representations of event sequences (Meck, 2003), tying the past and present environment together. There is a wide range of behaviors that depend on the ability to time short intervals.

Scalar expectancy theory (SET) is the leading contemporary theory of time estimation. This theory describes the behavior produced when humans and animals time intervals and compare them to "important" durations, i.e. those identified as a "standard" in human studies or those associated with reinforcement in animal studies. There are three information-processing stages in the SET model. First, a clock stage transforms subjective time into objective time using a pacemaker, a switch, and an accumulator. The pacemaker emits pulses at a certain rate and the switch signals the accumulator to count the pulses when a duration needs to be timed. The next stage of the scalar timing model is the memory stage, which consists of two memory registers for the storage of temporal information. The accumulator loads directly into working memory, which provides a buffer for temporal information from the current event that can be compared to a reference memory of timing information from previous events. In the third stage, a comparator uses a decision rule to determine whether the intervals in working memory and the reference memory store are the same. The decision rule depends on the type of timing task, but involves a ratio comparison of the intervals in the memory stores.

Studies of scalar expectancy theory indicate that these processing stages can be manipulated. For instance, several lines of research support the notion that arousal manipulations can influence the rate of the pacemaker of the internal clock (Penton-Voak, Edwards, Percival, & Wearden, 1996). The strongest evidence comes from studies of state-change with animal subjects (Maricq, Roberts, & Church, 1981; Meck, 1983). In these studies, several trials were administered so that a representation of some critical duration (such as that associated with reinforcement) was stored in long-term reference memory. In a subsequent timing task, the animal made a decision to respond based upon the similarity between a current duration and the long-term representation of the critical duration. When the reference memory was developed under a normal state and then the speed of the internal clock was increased with a stimulant drug, the representation of the current duration was generated by a faster clock. The rats responded early relative to the critical duration, a shift in behavior that differed from the condition in which both durations were generated with the clock running at the same speed (e.g. both clocks running normally or both clocks running faster).

Analogues of this experimental timing procedure, known as temporal generalization, have been developed for humans. In one example, a participant is presented with a duration that has been identified as the "standard." Blocks of stimuli are then presented that are shorter than, longer than, or equal the standard. After each comparison stimulus is presented, the participant indicates whether or not it was the same duration as the standard. The proportion of stimuli identified as the standard is plotted against the stimulus duration, forming a temporal generalization gradient. These functions typically peak at the standard and decline as the distance between the comparison duration and the standard duration increases.

Similar to the effects of drugs in animal timing, speeding up the internal clock results in systematic changes to the way humans respond to temporal generalization tasks. For example, exposing a participant to a series of loud clicks known as a "click train" prior to timing durations raises arousal and alters the subjective length of stimuli. Similar results are seen following increases in body temperature (see Wearden & Penton-Voak, 1995, for a review) or exposure to visual flicker (Droit-Volet & Wearden, 2002). Reductions in arousal have also been associated with changes in internal clock speed and timing behavior. For instance, a decrease in arousal over the course of repeated testing altered performance on temporal generalization tasks (Wearden, Pilkington, & Carter, 1999). Longer stimuli were identified as the standard as the test progressed, which was associated with a systematic decline in a self-report measure of activation. In another study, participants' arousal level was decreased by spacing the experimental trials 10s apart (Wearden, 2008). Throughout the course of the experiment, longer stimuli were identified as the standard to a greater extent, which was referred to as "subjective lengthening". Again, timing performance correlated with changes in self-reported levels of activation.

As mentioned, experimental manipulations that change arousal levels are thought to affect timing behavior through their influence on the pacemaker component of the internal clock. According to Wearden et al., 1999, generalization gradient shifts occur because participants initially encode the standard duration as n "ticks" from a pacemaker that runs at a constant rate, r. When arousal increases, r speeds up and emits the n ticks at a faster rate. For example, if a reference memory of 400ms is developed under a normal state and comparison durations are presented when the clock had sped up, the n ticks that are associated with the standard are accumulated in a shorter time period (e.g., 350ms). The higher frequency of responses at shorter

intervals shifts the temporal generalization gradients to the left. Decreases in arousal have the opposite effect. As the testing phase proceeds, arousal falls and r decreases, emitting the n ticks at a slower rate. It requires longer and longer stimuli to provide the n ticks that a participant has encoded as the standard duration and the generalization gradients shift to the right.

Scalar expectancy theory has not been examined in the context of physical activity, but there is evidence that acute exercise would influence temporal generalization. Acute exercise has arousing effects on both central and peripheral systems (Wittert, 2000) and might influence the internal clock in a similar manner. Previous research has shown that exercise has an influence on interval production, one of the more "classic" timing tasks. Vercruyssen, Hancock, & Mihaly (1989) evaluated participant's performance on a 10 second unfilled time interval production task before, during, and after exercise on a cycle ergometer. Timing performance was compared at two relative exercise intensities: 30 and 60% VO_{2max}. The participants underestimated a 10 second interval by 3.8% during exercise, independent of intensity. The underestimates were consistent with a faster internal clock speed, where the "ticks" that would normally represent 10 seconds were emitted more quickly during exercise. Additional support for the influence of acute exercise on timing comes from studies of critical flicker fusion thresholds during and after exercise. Flicker fusion tasks measure two forms of elementary time experiences: the threshold that is required for two events to be distinguished as separate events (successiveness) rather than fused as one event (simultaneity) (Fraisse, 1984). Flicker fusion thresholds improve gradually during moderate intensity exercise, peaking after about 20 minutes (Lambourne, Audiffren, & Tomporowski, 2010). Improvements in critical flicker fusion threshold after moderate and intense exercise have also been reported in several studies (Al-Nimer & Al-Kurashy, 2007;

Davranche & Pichon, 2005; Davranche, Burle, Audiffren, & Hasbroucq, 2005; Presland, Dowson, & Cairns, 2005; Shanmugam & Narayanan, 1973).

The primary purpose of this study was to examine the effect of acute exercise on temporal generalization performance. Exercise was expected to affect performance on temporal generalization tasks in a manner similar to other manipulations that increase arousal, speeding up the internal clock and shifting generalization gradients to the left. Further, it was predicted that subjective lengthening of the stimuli associated with decreased arousal as the task progresses would not occur during exercise. The second purpose of this study was to examine the locus of the effect of the arousal manipulation on the components of the scalar timing model. Although arousal manipulations (e.g. drugs, stress) purportedly influence the pacemaker of the internal clock (Penton-Voak et al., 1996), there is evidence that exercise has an influence on another component of the model: working memory. Some studies have shown that acute exercise can influence certain aspects of working memory (Audiffren, Tomporowski, & Zagrodnik, 2008). However, others have shown impairment of working memory performance (Dietrich & Sparling, 2004) or no effect (Coles & Tomporowski, 2007; Tomporowski & Ganio, 2006). Changes in working memory as a result of exercise-induced arousal would indicate that exercise might have an influence on multiple components of the scalar timing model.

To test these hypotheses, two temporal generalization tasks and one working memory task were administered during exercise and rest. The temporal generalization tasks were adapted from previous studies that have examined the influence of arousal on temporal generalization (Wearden et al., 1999; Wearden & Bray, 2001) and included a multiple-trial referenced task and an episodic (single-trial referenced) task. The multiple-trial referenced timing task involved the comparison of a series of durations to "fixed" standards that had been established in reference

memory. This task and several variants have been widely used in the literature, and performance has been linked to arousal level. For the episodic temporal generalization task, participants compared the duration of two stimuli on each trial. The duration of the stimuli was not repeated except by chance to prevent the formation of a reference memory. Because both stimuli are timed with the clock running at the same speed, an arousal manipulation that changes clock speed should not influence performance on this task. The Random Number Generation task was used to assess changes in working memory, and was administered immediately after the temporal generalization tasks were performed. The Random Number Generation task is associated with executive control and taps into two executive functions, inhibition and updating. To determine whether any exercise-induced changes in working memory persist after exercise as the participants' arousal levels returned to resting values, an Operation Span task was administered immediately after exercise. If exercise had an influence on the multiple-trial referenced task but not the working memory task, this would provide support for the effect of acute exercise on the internal clock component of the scalar timing model.

Methods

Participants. Sixteen healthy male and female college students (age 18-26) who engaged in regular physical activity were recruited for this study. During the first session, the participant signed an informed consent document that was approved by the university's Institutional Review Board. Next, the participant completed a medical history which screened for the following exclusion criteria: (1) any contraindications to maximal aerobic training based on ACSM guidelines (i.e., cardiovascular complications; neuromuscular, musculoskeletal, or rheumatoid disorders), (2) any use of psychoactive drug (e.g., anti-depressants), (3) physician-diagnosed mood disorder, and (4) pregnancy, seizure disorder or history of migraines. Finally, a physical

activity questionnaire (Kohl, Blair, Paffenbarger, Macera, & Kronenfeld, 1988) was administered to confirm that participant engaged in regular physical activity. Demographic data for the participants is presented in Table 4.1.

Procedure. The session continued if no contraindications to exercise were identified via the medical history questionnaire. First, the participant was familiarized with the cognitive tasks while seated on the cycle ergometer. Further detail about this training is provided in the following section. The participant then completed a graded exercise test to provide a measure of peak oxygen consumption and ventilatory threshold (VT). After a 5 minute warm up at 25 W, the work-rate began at 50 Watts (W) and increased continuously at a rate of 24 W/minute. Ventilation, oxygen uptake, carbon dioxide production, and respiratory exchange ratio were measured every 15 seconds with open-circuit spirometry. Heart rate (HR) was continuously measured using a Polar HR monitor (Polar Electro Oh, Kempele, Finland). Perceived exertion was measured using Borg's 15-point category scale (Borg, 1998). VO_{2peak} was defined by meeting two of the following three criteria: (1) HR within 10 beats/minute of age-predicted maximum, (2) respiratory exchange ratio above 1.10, (3) and perceived exertion above 17. VO_{2peak} was measured to standardize the subsequent cycling exercise bouts to the same relative percentage of each participant's VO_{2peak} and ventilatory threshold (VT).

At the end of this session, the participant was instructed to refrain from drinking caffeinated beverages or taking any medication before the next testing session. The three subsequent experimental sessions involved performing temporal generalization tasks and working memory tasks prior to and during cycling exercise at 90% of the participant's VT, and performing the same tasks during a resting control condition. In one session, the participant performed a multiple-trial referenced timing task and the RNG task prior to and during the last

10 minutes of a 35-minute exercise bout. In another session, the participant performed an episodic temporal generalization task and RNG task before a 35-minute exercise bout and during the last 10 minutes of exercise. Finally, the participant performed both temporal generalization tasks and the RNG task prior to and during a resting control condition of the same duration as the exercise bout. The order of the testing sessions was counterbalanced across participants, as well as the order of timing tasks during the rest session.

The exercise sessions consisted of initial temporal generalization and working memory task administration, a 5-minute warm-up cycling at 30% VO_{2peak}, and 30 minutes of cycling at 90% of VT. Measures of heart rate were obtained every five minutes throughout the session. The same timing task and working memory task were administered again after the participant had been cycling for 20 minutes at 90% VT. The temporal generalization tasks required approximately 10 minutes to complete, and were followed by a RNG task that required about 1.5 minutes to complete. On the first of the two exercise days, the Operation Span task was administered prior to the baseline testing and again during recovery from exercise. This task was included to examine whether any changes in working memory persisted after the exercise bout.

In the resting control condition, the participants performed the initial Operation Span task followed by the two temporal generalization tasks and the Random Number Generation task. Initial testing was done with the participant seated on the ergometer. The participant remained seated on the ergometer for the same duration as the exercise sessions (25 minutes) with no pedaling. After 25 minutes had elapsed, the participant performed the two temporal generalization tasks and the RNG task. This was followed by the Operation Span task.

Temporal Generalization Tasks. The temporal generalization tasks were programmed using SuperLab 4.0.5 (Cedrus Corporation, San Pedro, CA). The multiple-trial referenced task

used was similar to those used in previous research where two standards (300ms and 600ms) were encoded (Jones & Wearden, 2004). This permitted examination of superposition and the nature of the arousal effect. Participants were presented with orienting instructions followed by five presentations of the standard stimulus. A visual stimulus was used which consisted of a 14 \times 14 cm light-blue square presented in the center of the computer screen. Presentations of the standards were spaced by times drawn randomly from a uniform distribution running from 2000ms to 3000ms. The standard presentations were followed by a test phase in which the standard durations were presented along with non-standard duration values. Each block consisted of 11 trials, with three presentations of the standard and eight presentations of non-standard durations in a random order. The non-standard durations were logarithmically spaced around the standard and were 142, 182, 234, 252, 357, 385, 495, and 635ms in duration for the 300ms standard. The non-standard durations were 283, 364, 467, 504, 715, 770, 989, and 1270ms for the 600ms standard. The participant was prompted to "Press any key for next trial" to produce each stimulus in the block. Each key press was followed by a random delay sampled from a uniform distribution running from 1500 to 2500 ms, then the stimulus presentation. The display "Did that stimulus have the same duration as the standard? Press YES or NO" followed the stimulus, and participant made his or her response.

During the first session, the participant received training on the multiple trial referenced task. The training task consisted of 10 blocks of trials with the 300ms standard. The standard was presented five times prior to the test blocks and response feedback was provided on the first five blocks (the words, "CORRECT" and "INCORRECT," presented in green and red letters, respectively, for 250ms). Then, the same amount of standard presentations, trials, and feedback were presented for the 600ms standard. Performance on the training task was evaluated and

additional practice was given until the proportion of *yes* responses to the standard durations was 70%. Training was given to ensure that the participant established the standards in reference memory so that they could be identified when the task was administered without additional presentations of the standards (i.e. during the exercise/rest condition).

Shorter versions of this task were used during the remaining experimental sessions that featured the multiple-trial referenced task and feedback was no longer provided. Prior to rest or exercise, each standard was presented five times, followed by 12 blocks of trials alternating between the 300ms and 600ms standard. This allowed the participant to encode the reference memory of the standards prior to the experimental manipulation. Before each block, a message on the screen informed the participants which standard to use (short or long). During the exercise (or resting control period), the task format was identical to the training task performed earlier in the session with the exception that the standards were not presented again. This prevented the participant from re-calibrating his or her reference memory of the standard allowed performance to be affected by changes in arousal to a similar degree. Different versions of the task were used during each administration to prevent learning effects. The task versions were counterbalanced across participants.

The episodic temporal generalization task was adapted from Wearden and Bray (2001). The stimulus used was identical to that used in the multiple trial referenced task (a visual stimulus consisting of a 14×14 cm light-blue square presented in the center of the computer screen). This task involved a series of trials in which two stimuli were presented, separated by a 400-600ms interstimulus interval. After the second stimulus was presented, the participant was asked to judge whether the stimuli had the same duration, responding by pressing the YES or NO

keys. On each trial, a sample stimulus duration was randomly selected from three duration ranges: short (300-500ms), medium (450-750ms), and long (600-1000ms). The duration of the comparison stimulus was determined by multiplying the first duration by one of the following equally likely values: 0.25, 0.5, 0.75, 1, 1.25, 1.5, and 1.75. The order of presentation of the stimulus and comparison intervals was randomly varied between trials. Each block of 21 trials included each of the seven multipliers combined with the three duration ranges (short, medium, and long). For initial familiarization, four blocks of 21 trials were administered with feedback provided on the first two blocks. During the experimental session, each test consisted of four blocks of 21 trials for a total of 84 testing trials. Different versions of the task were used during each administration and were counterbalanced across participants.

Working memory tasks. The tasks used to measure working memory were the Random Number Generation task and the Operation Span task. To perform the Random Number Generation task, the participant generated a string of numbers that was as random as possible. The instructions given to the participant were identical to those used by Audiffren et al. (2009). The task was timed, and each number was cued by a computer-generated tone that sounded once per second. Each block consisted of 100 tones. The participants performed three blocks during the familiarization session, and one trial of 100 numbers was administered after each temporal generalization task during the experimental sessions. Participant responses were recorded by hand and then inputted into a computer-based analysis program (RGCalc) developed by Towse and Neil (1998). The RGCalc program provides multiple measures of randomness. A subset of indices was selected as measures of inhibition and updating. The inhibiting component indices included the Turning Point Index (TPI); variability in phase lengths (Runs); and Adjacency (A).

The updating component was measured by: Redundancy (R); Coupon; and Mean Repetition Gap (Mean RG).

The Operation Span task was adapted from Turner and Engle (1989), and involved solving a series of arithmetic equations while attempting to maintain a list of unrelated words in memory. The task was programmed using Superlab (Cedrus Corporation, San Pedro, CA). A series of nine equation-word combination strings (e.g. $(5 \times 2) - 1 = 8$? HOUSE) were presented one at a time on a computer. The words were concrete, one-syllable words. The participant was asked to read the equation aloud, verify whether or not the equation was correct, and read the word. At the end of the series, the participant attempted to write down the series of words in the order they were presented. Each series consisted of a random number of strings between three and six. Scores could range from 0 to 42, and points were only awarded for words recalled correctly and in the correct order. Four separate versions of the Operation Span task were used, and the word lists and series length were randomized for each test. Past research has demonstrated that the operation span has good test-retest reliability (0.88, Klein & Fiss, 1999) and validity (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002).

A verbal time estimation task was also included to confirm findings of previous research that showed exercise-related differences in verbal time estimation (Vercruyssen et al., 1989). The participant was cued to provide a verbal report of the time from the commencement of exercise (or the rest period) to the presentation of the cue. The cue consisted of an experimenter stating, "please estimate the cycling/rest duration," which occurred once during each 5-minute period of cycling/rest on a variable interval schedule. The timing of the cue was randomized within each 5minute block to avoid regularity and predictability of the intervals. Estimates were not requested during the administration of the temporal generalization and the Random Number Generation

tasks. After the tasks were completed, the participant was asked to provide a verbal estimate of the entire exercise/rest session. A ratio was calculated by dividing the estimate by the actual time, with a value less than one indicative of an underestimate and a value greater than one indicative of an overestimate.

Data analysis. For the multiple-trial referenced timing task, generalization gradients were plotted for the two standards and the data examined for superposition. Generalization gradients were also plotted for the episodic temporal generalization task across short, medium, and long durations. For both tasks, ANOVAs were used to examine the proportion of yes responses at each stimulus length presented during the exercise and control sessions. The first analysis examined the condition, stimulus, and interaction effects on the multiple-trial referenced timing task. This analysis consisted of a within-subjects 2 (condition: rest, exercise) by 2 (duration range: short, long) by 9 (stimulus duration) ANOVA with repeated measures on all factors. Data for the short and long duration ranges were then analyzed separately. The analysis for the short duration data consisted of a within-subjects 2 (condition: rest, exercise) by 9 (stimulus duration: 142ms, 182ms, 234ms, 252ms, 300ms, 357ms, 385ms, 495ms, 635ms) ANOVA with repeated measures on both factors. The same analysis was repeated with the data from the 600ms standard (283ms, 364ms, 467ms, 504ms, 600ms, 715ms, 770ms, 989ms, and 1270ms). Subjective lengthening of estimates was analyzed after the data from the 300ms standard and 600ms standard blocks were collapsed. Performance across blocks of trials was compared using a within-subjects 2 (condition: rest, exercise) by 2 (stimulus length: short, long) by 6 (block) ANOVA with repeated measures on all factors. The episodic temporal generalization task was analyzed using a 2 (condition: rest, exercise) by 7 (stimulus multiplier: 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75) ANOVA with repeated measures on all factors. The HuynhFeldt approach was used to correct for violations of sphericity when applicable, and t-tests with a Bonferroni correction for multiple comparisons were used to examine significant differences from ANOVAs.

For the Random Number Generation task, the turning point index, variability in phase lengths, and adjacency were calculated as measures of inhibition. The updating function was assessed through calculations of redundancy and mean repetition gap. Scores on these measures were compared using a 3 (condition: rest, first exercise bout, second exercise bout) by 2 (time: pre, during) ANOVA with repeated measures on both factors. The Operation Span scores were calculated for the tests administered prior to and after the resting control condition and the first exercise session. These scores were compared with a repeated-measures 2 (condition: rest, exercise) by 2 (time: pre, post) ANOVA. Finally, verbal estimates were converted to ratios (estimated time divided by actual time) and the ratios from the exercise sessions were averaged. These scores were compared to the scores from the rest condition using a 2 (condition: rest, exercise) by 7 (estimate block: minutes 0-5, 6-10, 11-15, 16-20, 20-25) ANOVA with repeated measures on both factors. All analyses were performed using SPSS version 17.0.

Results

The ANOVA performed on the scores from the multiple trial referenced task revealed a significant main effect for stimulus duration (F $_{8,120}$ = 40.41, p < 0.001, η^2 = 0.94), indicating that different stimulus durations produced different proportions of *yes* responses and that the participants were sensitive to comparison duration. The main effect for stimulus range was significant (F $_{1,15}$ = 9.72, p = 0.007, η^2 = 0.39), meaning the participants responded differently to the 300ms and 600ms standard. The significant main effect for stimulus range indicated that the data did not superimpose (see Figure 4.1, top panel). The main effect for condition was non-

significant (F _{1,15} = 0.57, p = 0.46), and the two-way interaction between condition and stimulus range was also non-significant (F _{1,15} = 0.09, p = 0.77). There was a statistically significant twoway interaction between condition and stimulus duration (F _{8,120} = 3.21, p = 0.02, η^2 = 0.94). This interaction is the critical statistic for demonstrating changes in internal clock speed because leftward or rightward shifts of the generalization gradient would require the exercise condition to have a differential effect on responses to stimuli longer than the standard than on stimuli shorter than the standard. The two-way interaction between stimulus range and stimulus duration was also significant (F _{8,120} = 7.32, p < 0.001, η^2 = 0.33), thus, the proportion of *yes* responses at the varying comparison stimuli was dependent on the length of the standard. Finally, the three-way interaction between condition, stimulus range, and stimulus duration was non-significant (F _{8,120} = 1.70, p = 0.13). Stability across the test administrations was acceptable (ICC _{3,4} = 0.86, 95% CI = 0.73 to 0.94).

The ANOVA performed on the scores from the 300ms temporal generalization task revealed a significant main effect for stimulus duration ($F_{8, 120} = 21.97$, p < 0.001, $\eta^2 = 0.60$). The main effect for condition (exercise, rest) was not significant ($F_{1,15} = 0.49$, p = 0.50). The twoway interaction between stimulus duration and condition was nearly significant ($F_{8,120} = 2.35$, p = 0.05, $\eta^2 = 0.13$). The ANOVA performed on the scores from the 600ms temporal generalization task revealed a statistically significant main effect for stimulus duration ($F_{8,120} = 31.71$, p < 0.001, $\eta^2 = 0.68$). The main effect for condition was not significant ($F_{1,15} = 0.20$, p = 0.66). The two-way interaction between stimulus duration and condition was significant ($F_{8,120} = 2.96$, p = 0.01, $\eta^2 = 0.17$). The generalization gradients for the 300ms and 600ms standard are plotted in Figure 4.1 (center and bottom panel, respectively). To further examine the gradient shifts, the median was calculated for the distribution of responses for each standard and condition. Prior to calculating the median, the number of yes responses to the standards was divided by 3 because the standards were presented 3 times more often. The medians for the 300ms standard were not different during exercise and rest ($t_{16} = 1.73$, p = 0.10). However, for the 600ms standard, the median was significantly shorter during exercise than during rest ($t_{16} = 2.42$, p = 0.03). The median of the response distribution was 570.19 (SD=100.28) during exercise and 635.16 (SD=78.77) during rest.

The analysis of subjective lengthening revealed a statistically significant interaction between condition and stimulus length ($F_{1,15} = 5.84$, p = 0.03, $\eta^2 = 0.28$), and repeated measures t-tests indicated that there were significantly fewer responses to stimuli shorter than the standard during rest ($t_{15} = -3.83$, p = 0.002). There was also a significant interaction between stimulus length and block ($F_{5,75} = 4.43$, p = 0.002, $\eta^2 = 0.23$) that resulted from fewer *yes* responses to shorter stimuli during Block 4 ($t_{15} = -3.56$, p = 0.003). The three-way interaction between condition, stimulus length, and block was non-significant ($F_{5,75} = 0.43$, p = 0.42). Exercise did not result in differential performance across the blocks for the two stimulus lengths. If exercise had prevented subjective lengthening, an interaction would have been present due to fewer responses to the longer stimuli in later test blocks during exercise.

Data for the episodic task during exercise were lost for one individual due to the participant feeling ill during the exercise bout. The ANOVA performed on the data from the episodic temporal generalization task revealed a significant main effect for stimulus multiplier $(F_{6,84} = 92.70, p < 0.001, \eta^2 = 0.98)$. The main effect for condition was not significant $(F_{1,14} = 0.16, p = 0.69)$, nor was the two-way interaction between stimulus multiplier and condition $(F_{6,84} = 1.03, p = 0.41)$. The generalization gradients for the data collapsed across stimulus range during exercise and rest are plotted in Figure 4.3, with little difference apparent between the

conditions (top panel). The gradients plotted across the different stimuli ranges (short, medium, long) during exercise and rest are also plotted in Figure 4.3 (center and bottom panel, respectively).

No significant main effects or interactions emerged for any of the Random Number Generation indices, including the TPI, Coupon, Runs, Redundancy, Adjacency, and Mean Repetition Gap. The means and standard deviations for the RNG task can be found in Table 4.2. Analysis of the OSPAN scores indicated that exercise had no effect on this task. The pre-exercise mean was 28.13 (SD = 5.63), the post-exercise mean was 28.06 (SD = 6.35), the pre-rest mean was 27.88 (SD = 5.30), and the post-rest mean was 28.94 (SD = 5.58). The main effects of condition and time were non-significant, as was the two-way interaction.

To analyze the verbal estimate data, ratios were computed for the estimated time and the actual time elapsed. The ratios from the exercise sessions were averaged and compared to the ratios from the rest session. There were no statistically significant main effects for condition or time. The two-way condition by time interaction was also non-significant. These ratios are plotted in Figure 4.4.

Heart rate and ratings of perceived exertion were similar for the two exercise days; these values were collapsed and can be found in Table 4.3 with the values from the rest session. While the participant was instructed to pedal at a freely chosen rate to minimize distraction during the cognitive tasks, RPM was measured every 5 minutes during the exercise bouts to ensure that he or she maintained a constant pedaling rate. RPM did not change between the exercise portion and cognitive testing portion of the exercise sessions.

Discussion

Temporal generalization tasks were used to test several hypotheses concerning the effects of exercise on timing behavior. During exercise, an increased internal clock speed was expected to cause shorter intervals to be mistaken for durations encoded as "standards" on a multiple trial referenced task. It was also predicted that exercise would prevent the participants from mistaking longer intervals for the standards as the task progressed. Exercise-induced arousal was not expected to affect performance on an episodic task, where the durations that were compared were timed with the internal clock running at the same speed. Finally, exercise was not expected to influence performance on working memory tasks administered in close temporal proximity to the timing tasks, providing support for the influence of arousal on the speed of the internal clock.

Consistent with the hypothesis that exercise-induced arousal would lead participants to mistake shorter intervals for the standard on a multiple-trial referenced task, generalization gradients for this task shifted to the left during exercise. However, exercise had no effect on the subjective lengthening of stimuli that typically occurs as the test progresses. As predicted, exercise had no impact on an episodic temporal generalization task that would not be sensitive to an arousal manipulation. Because this task is more dependent on working memory and no effect of exercise was observed on the working memory measures, this study identified the internal clock as the component of the scalar timing model that is affected by acute exercise.

The multiple trial referenced task included a 300ms and 600ms standard to examine superposition and determine the nature of the arousing effect of exercise. For the 300ms standard, the generalization gradient peaked at 357 ms during rest but peaked at the standard during exercise. This is an absolute leftward shift of 57 ms. For the 600ms standard, the gradient peaked at the standard during rest but peaked at 504ms during exercise. This leftward shift was

96 ms in absolute time. Because the shift doubled in absolute time when the duration being timed doubled, these findings are consistent with the internal clock running at a faster speed during exercise. The effect of the exercise manipulation was multiplicative, as the shifts were different in absolute time but approximately the same in relative time. This is indicative of a pacemaker speed effect. When the pacemaker is "sped up" by an experimental manipulation, the effect will be absolutely greater at longer times than at shorter times. In contrast, switch effects are additive and constant no matter the duration values employed (Droit-Volet et al., 2002). This indicates that exercise is similar to other arousal manipulations in that the pacemaker component of the internal clock is affected and not the switch component.

Previous research on temporal generalization performance examined peak shifts using the proportion of yes responses to the varying stimulus durations, consistent with the analysis just described. However, the medians of the response distributions were also compared for each standard. The medians during exercise and rest were significantly different only for the 600ms standard. The 300ms standard might have been too difficult to discriminate and therefore not sensitive to the arousal manipulation. Alternatively, researchers have suggested that arousal manipulations influence the timing of longer durations more than shorter durations (Penton-Voak et al., 1996).

The generalization gradients for the multiple trial referenced task did not demonstrate superimposition because performance was different for the 300ms standard and the 600ms standard. The failure to find superposition has been demonstrated in previous studies using a "changing standard" temporal generation task in which multiple standards were used that changed on each block (Jones & Wearden, 2003; 2004). This finding is of interest because failures to demonstrate superposition are rarely found with non-counting timing tasks. In fact,

even variations of temporal generalization tasks such as the episodic temporal generalization task produce superposition. The reason that the changing standard method of temporal generalization produces behavior that violates superposition is unknown (Jones & Wearden, 2004). It has been suggested that the different standards may interfere with each other in some way (Wearden & Lejeune, 2007).

Contrary to the hypothesis, exercise-induced arousal did not prevent subjective lengthening of stimuli during the multiple-trial referenced task. In fact, subjective lengthening was not evident in either condition. The task used in the present study was not a direct replication of the tasks used in Wearden et al.'s studies and the differences may account for the lack of subjective lengthening. It was shorter in overall duration (10 minutes rather than 20 minutes) and switching standards between blocks may also have influenced performance. When averaged across blocks, the proportion of yes responses to the short stimuli was the same as the proportion of yes responses to the long stimuli during exercise. During rest, there were fewer responses to the shorter stimuli. This interaction is consistent with the previous analysis in which the proportion of *yes* responses at the varying stimulus durations was dependent on whether the participant was resting or exercising.

The hypothesis that exercise would not affect performance on the episodic temporal generalization task was supported. Based on scalar timing theory, performance on this task would not be influenced by arousal manipulations that influence the pacemaker component of the internal clock because the standard and comparison duration were always presented within 600ms of each other. Unlike the multiple-trial referenced task, the close temporal proximity of the durations in the episodic task meant that the internal clock was purportedly running at the same speed when the durations were timed. Because the performance on the episodic task is also

independent of the formation of a reference memory, any alterations in performance on this task would result from changes in the other components of the scalar timing model. The absence of change on this task suggests that acute exercise has no influence on either the working memory component of the model or the decision stage. This is consistent with the evidence that acute exercise has little impact on working memory. Audiffren et al. (2009) showed that updating and inhibiting components of working memory are only altered during the first few minutes of exercise when the body is adjusting to the demands of initiating body movement. Lambourne et al. (2010) found no differences in performance during or following exercise on the Paced Auditory Serial Addition Task, which measures the updating component of working memory. Consistent with these studies, changes in working memory performance were not observed in any of the other working memory measures whether measured during exercise or following exercise or following exercise. Again, this provides support for the notion that exercise-induced arousal has an impact on the pacemaker component of the internal clock and not the working memory component of the model.

A novel contribution of this study is the data from the verbal estimation task. Only one study could be identified in which verbal estimation was examined during exercise (Vercruyssen et al., 1989). In this study, participants were asked to verbally estimate a 10-second interval. The participants underestimated the interval by 3.8% during exercise, which is consistent with the internal clock running at a faster speed because the "ticks" associated with a 10-second interval are emitted at a faster rate. In the present study, participants were asked to estimate the duration of the exercise or rest bout as it progressed. The ability of the participants to estimate time in this manner was not affected by exercise. However, it may be the case that the participants were able

to estimate the bout accurately as it elapsed because they had prior knowledge about the approximate length of the experimental session.

In terms of the scalar timing theory, this study showed that exercise is another way to influence the speed of the pacemaker component of the internal clock. Exercise influenced temporal generalization performance in a manner similar to other arousal inducing stimuli, such as stimulant drugs in animal studies and auditory stressors (click trains) in human studies. The implied mechanism for the centrally arousing effects of exercise is the release of neuromodulators (Tomporowski, 2003). The catecholamine hypothesis has been widely cited in the area of acute exercise and cognition (Chmura, Nazar, & Kaciuba-Ulsciko, 1994; Peyrin, Pequignor, Lacour, & Fourcade, 1987; McMorris et al., 1999). According to this hypothesis, exercise increases cognitive arousal, which increases brain concentrations of norepinephrine and dopamine.

Exercise-related changes in dopamine levels would influence timing because dopamine has been implicated as a neurotransmitter involved in timing processes. Administration of a dopamine antagonist causes animals trained with reinforcement schedules to respond early (Baunez, Nieoullon, & Amalric, 1995; Meck, 1996). Similarly, humans who are administered haloperidol, a dopamine antagonist, are less accurate in making temporal discriminations (Rammsayer, 1999). The administration of haloperidol also impairs performance on a learningdependent time estimation task (Zirnheld et al., 2004). Humans with damaged dopamine systems (i.e. Parkinson's disease) have impaired performance on time perception tasks (Pastor, Artieda, Jahanshahi, & Obeso, 1992; Pastor & Artieda, 1996).

The results of this study also showed that individuals are able to encode standards for a multiple-trial referenced task and retain them for a period of 25 minutes, since generalization

gradients generally peaked at the standard after this period. The gradients also demonstrated the predicted leftward shifts when the temporal generalization tasks were performed during exercise. This is of interest because researchers in this area have suspected that participants are not actually using the standard for comparison but some "constructed" version of it such as the average of all stimuli presented (Wearden & Ferrara, 1995). This could be problematic when trying to examine the influence of changes in clock speed because the standard durations are timed with a normal clock and any differences in clock speed are either washed out or very difficult to observe once the participants are shown a series of comparison durations (Wearden, 2009, personal communication). However, this did not appear to be the case, which supports the notion that exercise is a viable way to manipulate clock speed and observe the resultant changes in temporal generalization performance.

Future research might provide additional support for the role of exercise on the internal clock by training a participant to identify the standard during exercise and determining whether generalization gradients shift to the right when the clock slows down after recovery from exercise. This type of experiment would be similar to the studies performed by Meck and colleagues in the early 1980's in which the influence of state changes was observed using drugs in animal subjects. It would also be of interest to examine whether exercise intensity influences the magnitude of gradient shifts on a multiple-trial referenced temporal generalization task.

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Figure 4.1. Generalization gradients for temporal generalization task performed during exercise and rest. Upper panel: proportion of *yes* responses plotted against stimulus duration for the rest and exercise conditions and the different stimulus ranges (300ms, 600ms). Center panel: data for 300ms standard. Lower panel: data for 600ms standard.



Figure 4.2. Timing measures derived from temporal generalization gradients. The data shown are mean proportion of yes responses to stimulus durations shorter than the standard (top panel) plotted against test block and the proportion of yes responses to stimulus durations longer than the standard (bottom panel).



Figure 4.3. Proportion of *yes* responses plotted against stimulus multiplier for episodic task performed during exercise and rest (top panel). Center panel: generalization gradients during exercise for the short, medium, and long duration ranges. Bottom panel: generalization gradients during rest for the short, medium, and long duration ranges.



Figure 4.4. Ratios of estimated time to actual time during exercise and rest. Data are means \pm standard error.

 Table 4.1. Participant characteristics.

	Males (N=8)	Females (N=8)
Age (yr)	21.12 (1.13)	21.00 (0.53)
$VO_{2peak} (ml \cdot kg^{-1} \cdot min^{-1})$	41.48 (6.17)	32.67 (8.44)
Anaerobic Threshold	2.37 (0.52)	1.23 (0.50)
Energy Expenditure (METh/wk)	51.26 (22.37)	37.25 (18.22)

Values are means (SD).

	Exercise		Rest
	MTR	Episodic	
TPI	90.24 (11.23)	94.27 (13.71)	92.10 (8.40)
Runs	0.87 (0.32)	0.78 (0.28)	0.81 (0.27)
Coupon	18.46 (4.96)	18.03 (3.92)	17.04 (4.48)
Adjacency	23.10 (9.56)	22.88 (9.31)	23.77 (7.71)
R	1.36 (0.99)	1.40 (0.81)	1.21 (0.84)
MRG	8.69 (0.18)	8.68 (0.16)	8.71 (0.21)

Table 4.2. Means and standard deviations for Random Number Generation indices.

	Exercise	Rest
Heart Rate	139.25 (18.66)	74.73 (8.70)
RPE	13.60 (2.29)	6.06 (0.25)
RPM	67.46 (9.54)	n/a
RPM during task	68.04 (9.49)	n/a

Table 4.3. Heart rate, ratings of perceived exertion, and revolutions per minute during experimental sessions. Data are means \pm standard deviation.
CHAPTER 4

EXPERIMENT 2: THE EFFECT OF ACUTE EXERCISE AND CAFFEINE ON

TEMPORAL GENERALIZATION

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Abstract

Objective: Temporal generalization is a technique used to examine timing behavior and the speed of the internal clock. The purpose of this study was to use a randomized, controlled trial to examine the effects of caffeine on temporal generalization performance at rest and during exercise. Methods: Thirty healthy, physically active college students were randomly assigned to a caffeine (5mg/kg) or placebo group. Each group performed a temporal generalization task involving two standards (300ms, 600ms) during moderate-intensity aerobic exercise. This task was also administered before and during a resting control condition that was approximately the same length as the exercise session. **Results**: Consistent with an increase in internal clock speed, generalization gradients for a 600ms standard shifted to the left during exercise. No statistically significant differences were present between the caffeine and placebo group for the task performed during exercise, potentially the result of gradients shifting in opposite directions during exercise and rest for the caffeine group. This pattern of timing behavior indicated that the participants in the caffeine group timed the standard intervals with the clock running at a faster speed. **Conclusions**: Timing performance was influenced by acute exercise and caffeine. Each appeared to speed up the internal clock, and caffeine may reduce interference between two standards under certain conditions. When the temporal generalization task was performed after caffeine had taken effect, caffeine had an influence on the variance of the timing measures but not clock speed, likely due to the participants in the caffeine condition re-calibrating their reference memory of the standard with a clock running at a faster speed.

Key words: scalar timing, physical activity, working memory, cognition, stimulant drugs

Introduction

The success of the scalar expectancy theory (SET) in explaining timing performance on certain tasks has revived interest in the idea of an internal clock. The SET theory describes the behavior produced when humans and animals time intervals and compare them to "important" durations, i.e. those identified as a "standard" in human studies or those associated with reinforcement in animal studies (Wearden & Bray, 2001). According to SET, the ability to make these duration judgments arises from an internal clock of a pacemaker-accumulator type. The success of the theory can be partially attributed to its ability to explain arousal influences on the internal clock system. Increases in arousal increase the rate of the pulses emitted by the system such that more pulses are emitted per unit of time, and decreases in arousal have the opposite effect (Penton-Voak, Edwards, Percival, & Wearden, 1996). These arousal manipulations systematically alter the subjective experience of time.

The best evidence of the influence of arousal on the internal clock comes from drug studies of state changes in animals (Maricq, Roberts, & Church, 1981; Meck, 1983). In these studies, several trials were administered so that a duration associated with reinforcement was stored in long-term reference memory. In a subsequent timing task, the animal made a decision to respond based upon the similarity between a current duration and the long-term representation of the critical duration. When the reference memory was developed under a normal state and then tested after the administration of methamphetamine or cocaine, the representation of the critical duration was generated by a faster clock. The rats responded early relative to the critical duration, a shift in behavior that differed from the condition in which both durations were generated with the clock running at the same speed (e.g. both clocks running normally or both clocks running faster).

A similar pattern of behavioral shifts can be observed in humans using a non-invasive arousal manipulation developed by Triesman, Faulkner, Naish, and Brogan (1990). These researchers studied the effects of repetitive stimulation in the form of clicks or flashes on duration judgments. The repetitive stimulation appeared to speed up the pacemaker, purportedly by increasing arousal. In a series of subsequent experiments, Penton-Voak et al. (1996) showed that the subjective duration of stimuli was increased by 10% when preceded by a train of clicks. Wearden, Philpott, and Win (1996) used click trains in an experiment similar to the drug studies from the 1980's (e.g. Meck, 1983) that examined shifts in duration judgments following state changes. The researchers used a pair comparison task in which the two stimuli presented on each trial were always the same. In one condition, the first stimulus was preceded by clicks and the second was not. In the second condition, the first stimulus was timed normally (no clicks) but the second duration stimulus was preceded by clicks. The effect on judgments of duration was consistent with relative speeding up and slowing down of the internal clock. In the first condition, the first tone was perceived as longer than the second because it was timed with a faster clock. The opposite was found in the second condition, where the second tone was timed with a faster clock and perceived as longer than the first tone.

Exercise-induced arousal may be another way to influence the internal clock, and the influence of exercise on the internal clock was explored in Experiment 1. Participants were trained to identify two standard durations (300ms, 600ms) on a temporal generalization task. The participants then performed the temporal generalization task during the last 10 minutes of a 35-minute bout of moderate cycling exercise. Generalization gradients shifted to the left when compared with the gradients obtained during a resting control session. This finding is significant

because researchers have been interested in non-invasive ways to influence the speed of the internal clock (Wearden & Penton-Voak, 1995).

Despite caffeine being a well-known arousal manipulation, research studies on the effect of caffeine on the internal clock are lacking. Studies of caffeine are of interest because caffeine is one of the most popular and widely consumed psychoactive substances in the world (James, 1997). As such, many physical and mental tasks are performed while individuals are under the influence of caffeine. Caffeine administration has been shown influence performance on certain types of timing tasks, such as verbal estimation and reproduction tasks. Acute caffeine administration has been shown to alter temporal estimates of longer durations, leading participants to underestimate time intervals when tested in the prospective paradigm (Gruber & Block, 2003). Low daily consumption of caffeine has been shown to improve the accuracy of prospective verbal time estimation humans (Stine, O'Connor, Yatko, Grunberg, & Klein, 2002). However, no studies could be located in which the effects of caffeine on temporal generalization performance were examined. It is likely that the arousing effects of caffeine would influence timing behavior and the most likely outcome would be a leftward shift in the generalization gradient due to an increased internal clock speed.

The subjective and behavioral effects of caffeine administration are similar to those that occur after administration of dopaminergically mediated stimulant drugs (e.g. cocaine, amphetamines). Examples include increased locomotor activity, discriminative stimulus effects, and the production of withdrawal symptoms. Caffeine is thought to exert dopamine agonist-like effects through action on dopamine receptors that are secondary to adenosine antagonism. Dopaminergic drugs have been strongly linked to changes in performance on timing tasks. Humans who are administered haloperidol, a dopamine antagonist, were less accurate in making

temporal discriminations (Rammsayer, 1999). The administration of haloperidol also impaired performance on a learning-dependent time estimation task (Zirnheld, Carroll, & Kieffaber, 2004). Humans with damaged dopamine systems have impaired performance on time perception tasks (Pastor, Artieda, Jahanshahi, & Obeso, 1992; Pastor & Artieda, 1996). Individuals with Parkinson's disease showed a pattern of deficits is consistent with a slowed internal clock when tested while off their medication (Gibbon, 1977; Malapani et al., 1998, Pastor et al., 1992).

Despite the interest in the effects of arousal manipulations on the internal clock and timing behavior, arousal manipulations have typically been studied in isolation. Little is known about the influence of multiple arousal manipulations on timing behavior. Combining the arousing effects of acute, aerobic exercise and psychostimulant drugs could result in different patterns of timing performance. This type of information would be of practical significance in military, occupational, and sports settings. For example, caffeine is a part of the daily rations supplied to soldiers, who make complex cognitive decisions while engaged in physical activity. Emergency response personnel such as firefighters make important time-based decision under physical duress, and are known to use caffeine to offset fatigue during periods of extended wakefulness. Finally, caffeine is widely used by professional and recreational athletes due to its well-known ergogenic properties, and sport performance is dependent on accurate timing of movements.

Therefore, the influence of caffeine administration on the internal clock is not known, and the effect of combining two arousal agents (such as caffeine and acute exercise) on interval timing has not been examined. Studying the effects of acute exercise and caffeine, alone and in combination, will provide additional information about how arousal manipulations influence the internal clock. Caffeine was expected to influence behavior in a manner similar to the way

exercise influenced behavior in Experiment 1, by speeding up the internal clock and shifting generalization gradients to the left. To examine this, 30 young adults were randomized to a caffeine (5mg/kg) or placebo (flour capsule) condition and a multiple-trial reference temporal generalization task was performed at rest and during exercise.

Methods

Participants. Thirty healthy male and female (15 M, 15 F) college students (age 18-26) who engaged in regular physical activity were recruited for this study. During the first session, the participant signed an informed consent document, which was approved by the university's Institutional Review Board. Next, the participant completed a medical history which screened for the following exclusion criteria: (1) any contraindications to maximal aerobic training based on ACSM guidelines (i.e., cardiovascular complications; neuromuscular, musculoskeletal, or rheumatoid disorders), (2) any use of psychoactive drug (e.g., anti-depressants), (3) physician-diagnosed mood disorder, and (4) pregnancy, seizure disorder or history of migraines. Finally, a physical activity questionnaire (Kohl, Blair, Paffenbarger, Macera, & Kronenfeld, 1988) was administered to ensure that participants engaged in regular physical activity. Demographic data for the participants are presented in Table 5.1.

Procedure. The session continued if no contraindications to exercise were apparent on the medical history questionnaire. First, the participant was familiarized with the cognitive tasks used in the study while seated on the cycle ergometer. The participant then completed a graded exercise test to provide a measure of peak oxygen consumption and ventilatory threshold (VT). After a 5 minute warm up at 25 W, the work-rate began at 50 Watts (W) and increased continuously at a rate of 24 W/minute. Ventilation, oxygen uptake, carbon dioxide production, and respiratory exchange rate were measured every 15 seconds with open-circuit spirometry.

Heart rate (HR) was continuously measured using a Polar HR monitor (Polar Electro Oh, Kempele, Finland). Perceived exertion was measured using Borg's 15-point category scale (Borg, 1998). VO_{2peak} was defined by meeting two of the following three criteria: (1) HR within 10 beats/minute of age-predicted maximum, (2) respiratory exchange ratio above 1.10, (3) and perceived exertion above 17. VO_{2peak} was measured to standardize the subsequent cycling exercise bouts to the same relative percentage of each participant's VO_{2peak} and ventilatory threshold (VT).

The participant was randomly assigned to an intervention group; one group was administered a dose of caffeine (5mg/kg) in capsule form and the other group was given a placebo (flour) in capsule form. Blocked randomization was used (Research Randomizer, <u>www.randomizer.org</u>) to ensure that a similar number of male and female participants were assigned to each condition. A double-blind procedure was used to reduce the odds of participant and experimenter expectancy effects. The drug treatment remained the same for each participant in each session. At the conclusion of the experiment, participants were asked to guess which condition they were in and were then informed of the drug condition to which they were assigned.

In the subsequent testing sessions, participants in both groups performed a moderate bout of cycling exercise at 90% VT and a resting control condition. The participant completed a questionnaire to ensure that they abstained from caffeine consumption for the past week, alcohol consumption for 24 hours, and exercising for 12 hours. A 5 mg/kg dose of caffeine or placebo was delivered in gelatin capsule form. The participant then waited 60 minutes, a duration that coincides with peak plasma caffeine concentrations (Kaplan et al., 1997). The participant was

allowed to read non-academic materials during this time period, and general-interest magazines (e.g. National Geographic) were provided.

Temporal Generalization Task. The multiple-trial referenced temporal generalization task was programmed using SuperLab 4.0.5 (Cedrus Corporation, San Pedro, CA). The task used was similar to those used in previous research where two standards were encoded (Jones & Wearden, 2004). This permitted examination of superposition and the nature of the arousal effect. Participants were presented with orienting instructions followed by presentations of the standard stimulus. A visual stimulus was used which consisted of a 14×14 cm light-blue square presented in the center of the computer screen. Presentations of the standards were spaced by times drawn randomly from a uniform distribution running from 2000ms to 3000ms. The standard presentations were followed by a test phase in which the standard durations were presented along with non-standard duration values. Each block consisted of 11 trials, with three presentations of the standard and eight presentations of non-standard durations in a random order. The non-standard durations were logarithmically spaced around the standard and were 142, 182, 234, 252, 357, 385, 495, and 635ms in duration for the 300ms standard. The nonstandard durations were 283, 364, 467, 504, 715, 770, 989, and 1270ms for the 600ms standard. The participant was prompted to "Press any key for next trial" to produce each stimulus in the block. Each key press was followed by a random delay sampled from a uniform distribution running from 1500 to 2500 ms, then the stimulus presentation. The display "Did that stimulus have the same duration as the standard? Press YES or NO" followed the stimulus, and participant made his or her response.

During the first session, the participant received training on the multiple trial referenced task. The training task consisted of 10 blocks of trials with the 300ms standard. The standard was

presented five times prior to the test blocks and response feedback was provided on the first five blocks (the words, "CORRECT" and "INCORRECT," presented in green and red letters, respectively, for 250ms). Then, the same amount of standard presentations, trials, and feedback were presented for the 600ms standard. Performance on the training task was evaluated and additional practice was given until the proportion of *yes* responses to the standard durations was 70%. Training was given to ensure that the participant established the standards in reference memory so that they could be identified when the task was administered without additional presentations of the standards (i.e. during the exercise/rest condition).

Shorter versions of this task were used during the remaining experimental and feedback was no longer provided. Prior to rest or exercise, each standard was presented five times, followed by 12 blocks of trials alternating between the 300ms and 600ms standard. This allowed the participant to encode the reference memory of the standards prior to the experimental manipulation. Before each block, a message on the screen informed the participants which standard to use (short or long). During the exercise (or resting control period), the task format was identical to the training task performed earlier in the session with the exception that the standards were not presented again. This prevented the participant from re-calibrating his or her reference memory of the standard allowed performance to be affected by changes in arousal to a similar degree. Different versions of the task were used during each administration to prevent learning effects. The task versions were counterbalanced across participants.

Data analysis. Generalization gradients were plotted for the multiple-trial referenced timing task and the data was examined for superposition. ANOVAs were used to examine the proportion of *yes* responses at each stimulus length presented during the exercise and control

sessions. The first analysis examined the group, condition, stimulus, and interaction effects and consisted of a 2 (group: caffeine, placebo) by 2 (condition: rest, exercise) by 2 (duration range: short [300ms standard], long [600ms standard]) by 9 (stimulus duration) ANOVA. Data for the short (300ms standard) and long (600ms standard) duration ranges were then analyzed separately. The analysis for the short duration data consisted of a 2 (group: caffeine, placebo) by 2 (condition: rest, exercise) by 9 (stimulus duration: 142ms, 182ms, 234ms, 252ms, 300ms, 357ms, 385ms, 495ms, 635ms) ANOVA with group as a between-subjects factor and repeated measures on the condition and stimulus duration factors. The same analysis was repeated with the long duration data (283ms, 364ms, 467ms, 504ms, 600ms, 715ms, 770ms, 989ms, and 1270ms). To examine whether the participants re-calibrated their reference memory of the standard with their clock running at a faster speed after caffeine was administered, temporal generalization performance was evaluated in the tasks administered prior to the exercise manipulation. Scores were collapsed for the tasks performed before exercise and before rest. This analysis consisted of a 2 (group: caffeine, placebo) by 2 (duration range: short, long) by 9 (stimulus duration) ANOVA with group as a between subjects factor and repeated measures on the duration range and stimulus duration factors.

Results

The ANOVA that examined the group, condition, stimulus, and interaction effects revealed a significant main effect for stimulus duration (F $_{8,224} = 62.37$, p < 0.001, $\eta^2 = 0.69$), indicating that different stimulus durations produced different proportions of *yes* responses and that the participants were sensitive to comparison duration. The main effect for stimulus range was non-significant (F $_{1,28} = .01$, p = 0.92), which indicated that the data superimposed (see Figure 5.1). The main effect for condition (exercise, rest) was non-significant (F $_{1,28} = 1.92$, p = 0.17), as were all other interactions. The two-way interaction between condition and stimulus duration would be the critical statistic for demonstrating changes in internal clock speed from exercise because leftward or rightward shifts of the generalization gradient would require the exercise condition to have a differential effect on responses to stimuli longer than the standard than on stimuli shorter than the standard. Furthermore, there was no significant difference in temporal generalization performance between the caffeine group and the placebo group (F _{1,28} = 0.13, p = 0.72), and the three-way interaction between condition, stimulus duration, and group was non-significant (F _{8,224} = 1.13, p = 0.35). The stability of the temporal generalization scores across the four administrations was high (ICC _{3,4} = 0.91, 95% CI = 0.85 to 0.95). The generalization gradients for each group are plotted Figure 5.2 for the 300ms (top panel) and 600ms (bottom panel) standard.

The ANOVA performed on the scores from the 300ms temporal generalization test blocks revealed a significant main effect for stimulus duration (F $_{8,224} = 48.27$, p < 0.001, $\eta^2 = 0.63$). The main effect for condition (exercise, rest) was not significant (F $_{1,28} = 1.22$, p = 0.28), nor was the main effect for group (F $_{1,28} = 0.001$, p = 0.97). None of the interactions was statistically significant. The ANOVA performed on the scores from the 600ms temporal generalization test blocks revealed a statistically significant main effect for stimulus duration (F_{8,224} = 32.37, p < 0.001, $\eta^2 = 0.54$). The main effect for condition was not significant (F_{1,28} = 0.70, p = 0.28), nor was the main effect for group (F_{1,28} = 0.37, p = 0.54). The two-way interaction between stimulus duration and condition was significant (F $_{8,224} = 2.72$, p = 0.02, $\eta^2 = 0.09$), indicating that exercise produced a shift in the generalization gradient (see Figure 5.3). None of the other interactions was significant.

The ANOVA performed on the scores from the temporal generalization tasks performed 60 min after caffeine and placebo administration revealed a statistically significant two-way interaction between stimulus range and group ($F_{1,28} = 7.53$, p = 0.01, $\eta^2 = 0.12$), indicating that the participants responded differently to the 300ms and 600ms standard as a function of caffeine administration. The two-way interaction between stimulus duration and stimulus range was statistically significant ($F_{8,224} = 6.99$, p < 0.001, $\eta^2 = 0.20$), indicating that there were differences in the way that participants responded to the varying stimulus durations based on whether the standard was 300ms or 600ms. The two-way interaction between group and stimulus duration was non-significant ($F_{8,224} = 0.69$, p = 0.57), as was the three-way interaction between group, stimulus duration, and stimulus range ($F_{8,224} = 1.40$, p = 0.23). The generalization gradients for the task performed prior to the exercise manipulation are plotted in Figure 5.3 for the 300ms standard (top panel) and the 600ms standard (bottom panel).

The percentage of participants in the caffeine condition who correctly identified the condition was at chance level (46%). All of the participants in the placebo condition correctly identified the condition.

Discussion

A double blind experiment was performed to examine the influence of acute exercise and caffeine on temporal generalization. Exercise was expected to increase the speed of the internal clock, causing generalization gradients to shift to the left. Caffeine was expected to have the same effect, and the largest leftward gradient shifts were expected when caffeine and exercise were combined. A temporal generalization task was administered that involved a 300ms standard and a 600ms standard. When performance on each standard was considered independently, exercise resulted in a leftward shift of the generalization gradient for the 600ms standard

consistent with a faster internal clock. This finding was a replication of the results from Experiment 1. However, exercise did not result in the predicted gradient shifts for the 300ms standard test blocks or the overall task. The combination and caffeine and exercise also did not elicit the expected effect because there were no statistically significant differences between the generalization gradients from the caffeine and placebo groups.

One notable difference between this experiment and Experiment 1 is that the behavior produced in this experiment conformed to the scalar property of variance. The scalar property of variance requires that timing sensitivity remains constant as the durations timed vary (Wearden & Lejeune, 2007), which is commonly tested by examining superposition. Superposition involves plotting measures of timed behavior from judgments of different absolute durations on the same relative scale. When timing behavior conforms to the scalar property of variance, the generalization gradients will superimpose. According to Wearden and Lejeune (2007), the quality of superposition is often determined by inspection of the plot although statistical tests can also be used. Visual inspection of Figure 5.1 shows the overlapping gradients for the 300ms and 600ms standard for the caffeine group (top panel) and placebo group (bottom panel), and the main effect for stimulus range (300ms, 600ms) was non-significant. When considering performance on the overall task in Experiment 1, the property of scalar variance was violated because the gradients did not superimpose (see Figure 4.1) and there was a statistically significant main effect for stimulus range, which indicated that performance differed for the 300ms standard and 600ms standard. As mentioned in the discussion of Experiment 1, violations of the scalar property of variance have been observed on tasks where the standard in force changes from block to block (Wearden & Lejeune, 2007).

This discrepancy could be the result of differences in the experimental procedure between the studies. In Experiment 1, the participants performed an episodic temporal generalization task as well as a multiple trial referenced temporal generalization task. If interference between the standards results in violations of superposition on tasks with multiple standards, the episodic task may have further interfered with performance on this task in Experiment 1. Another difference is that the experimental sessions were 60 minutes longer in the present study to allow for peak plasma caffeine concentrations (Kaplan et al., 1997). The additional time spent in the laboratory may have influenced arousal levels in such a way as to influence variability in timing measures. Performance on this type of task has been shown to be sensitive to decreases in arousal resulting from the passage of time (Wearden, 2008). As arousal levels fall, the comparison stimuli are timed by a slower clock, which results in the generalization gradients shifting to the right. This would affect the accuracy of timing measures, but the influence on the variability has not been reported in this type of study.

While superposition was present in the temporal generalization task performed during exercise, superposition was different for the caffeine and placebo groups on the task performed prior to the exercise manipulation. A statistically significant interaction between stimulus range and group in this task indicated that differential performance on the 300ms and 600ms standard was dependent on caffeine, and inspection of the data indicated that the gradients superimposed for the caffeine group but not the placebo group (see Figure 5.3). One explanation for this finding is that caffeine resulted in less interference between the standards. This would be consistent with the literature on the effects of caffeine on the information processing system. Caffeine administration modifies the information processing system to improve the processing of relevant stimulus characteristics (Kanwisher & Wojciulik, 2000; Lorist & Tops, 2003). These

changes can multiply the neural response to relevant information or diminish the impact of irrelevant information (Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999), thereby reducing interference between the two standards.

The first property of behavior that conforms to the scalar properties of timing is based on variance of timing measures, and the second property is based on the accuracy of mean timing measures. The property of mean accuracy describes the linear variation of the mean measures of timed behavior, such that the average time intervals produced or estimated by individuals are in line with the time requirement or actual stimulus duration, respectively. This property was violated for the 300ms standard when considering performance across the entire sample. The generalization gradients peaked at 357ms in both the rest and exercise condition. This property was also violated in the rest condition of Experiment 1, where the gradient peaked at 357ms for the 300ms standard. This finding may be explained by systematic variance in the switch component of the SET model. The switch can contribute variance to timing behavior that is due to variable latencies when starting and stopping, independent of the duration timed. Studies that have used short durations (less than 100ms) have produced behavior with increased relative variance that can be explained by the operation of the switch in the SET model. This variance would make a larger contribution to the timing of short intervals (Wearden & Lejeune, 2007). The greater variability present in timing the shorter intervals may result in more difficulty in timing them accurately. Alternatively, Penton Voak et al. (1996) report that arousal manipulations affect the timing of larger durations more than shorter ones.

While the participants were unable to produce gradients that peaked at the 300ms standard, the gradients were more consistent for the exercise conditions and groups when the 300ms standard was in force (see Figure 5.2). When examining the gradients for the task

performed during exercise and rest, there was more overlap for the 300ms standard than the 600ms standard. Because there was no shift in the gradients on the shorter standard, the nature of the arousal influence could not be determined. However, the results from Experiment 1 indicated that exercise had an effect on the pacemaker component of the internal clock. The leftward shift in gradient for the 600ms standard was similar to the shift observed in Experiment 1, being 115 ms in absolute time.

During exercise, the gradients for the 600ms standard for the caffeine and placebo group peaked at the standard. At rest, the gradient for the placebo group peaked at the 715ms comparison stimulus and the gradient for the caffeine group peaked at the 770ms comparison duration. This finding was in direct opposition to what was predicted because caffeine was expected to speed up the internal clock and produce leftward shifts in the gradients, even at rest. However, this finding can be reconciled with the scalar timing model. Because the participants in the caffeine condition were shown the standards after caffeine administration, these durations would have been timed with a putatively faster clock. This would mean that more "ticks" became associated with the standard. As the rest session wore on, arousal decreased, slowing the rate of the internal clock. If more ticks were generated when the standards were timed, it would require longer stimuli to produce the same number of ticks that had been previously associated with the standards. This would result in the generalization gradient shifting to the right.

The lack of gradient shifts in the task performed prior to the exercise manipulation is also consistent with the notion that the participants in the caffeine condition recalibrated their reference memory of the standard with the clock running at a faster speed. We had hoped to prevent this by providing the participants with training at the outset of the study. An alternative approach would be to allow the participants to time the standards prior to the caffeine

manipulation. The former approach was selected because the amount of time that participants can retain a reference memory is unknown. In previous studies of the influence of arousal on the internal clock, the arousal manipulation occurred in close temporal proximity to the timing of comparison tones (e.g. Penton-Voak et al., 1996). The results of Experiment 1 provided evidence that the standards could be retained for a period of 25 minutes. Due to the exploratory nature of this experiment, we opted to keep the protocol similar. Otherwise, the participants would have been required to retain the standard for the additional amount of time to allow the caffeine to take effect. Unfortunately, the participants appeared to adjust their reference memory of the standard to a faster clock speed, which would mask the effects of caffeine on temporal generalization. Future research could explore the length of time that participants can retain the reference memory of a standard to inform studies of arousal effects on clock speed involving longer arousal manipulations.

In summary, the results of this experiment show that acute exercise resulted in a shift to the left of temporal generalization gradient on a 600ms standard. This effect is consistent with the internal clock running at a faster speed during exercise. However, no shift occurred for the 300ms standard, and these gradients generally peaked at the comparison stimulus that was one step longer than the standard. For participants in the caffeine condition, the gradients peaked at the standard during exercise. During rest, the gradient shifted to the right and peaked at the comparison stimulus that was two steps longer than the standard. Theoretically, this shift could be the result of the standards being associated with more pulses from the pacemaker because the durations were timed with a faster clock. Longer stimuli would be required for these pulses to elapse after the clock had slowed down. This demonstrated the sensitivity of the internal clock to arousal manipulations such as acute exercise and caffeine.

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Figure 5.1. Generalization gradients for temporal generalization task performed during exercise and rest. Upper panel: proportion of *yes* responses plotted against stimulus duration for the rest and exercise conditions and the different stimulus ranges (300ms, 600ms) for the **caffeine** group. Lower panel: proportion of *yes* responses plotted against stimulus duration for the rest and exercise conditions and the different stimulus ranges (300ms, 600ms) for the **caffeine** group. Lower panel: proportion of *yes* responses plotted against stimulus duration for the rest and exercise conditions and the different stimulus ranges (300ms, 600ms) for the **placebo** group.



Figure 5.2. Generalization gradients for temporal generalization tasks performed during exercise and rest for caffeine and placebo groups. Upper panel: proportion of *yes* responses plotted against stimulus duration for the rest and exercise conditions for **300ms** standard. Lower panel: data for **600ms** standard.



Figure 5.3: Generalization gradients for 300ms and 600ms standard during exercise and rest, collapsed across group (caffeine, placebo).



Figure 5.4. Generalization gradients for temporal generalization task performed 60 min after administration of **caffeine** group (top panel) and **placebo** (bottom panel).

 Table 5.1. Participant demographics.

	Males (N=15)	Females (N=15)
Age (yr)	22.13 (1.19)	20.73 (1.50)
$VO_{2peak} (ml \cdot kg^{-1} \cdot min^{-1})$	40.23 (8.04)	36.19 (5.64)
Anaerobic Threshold	2.54 (0.47)	1.59 (0.38)
Energy Expenditure (METh/wk)	42.43 (30.85)	53.69 (27.97)

Values are means (SD).

	Exercise	Rest
Heart Rate	142.60 (18.32)	74.96 (10.20)
RPE	13.45 (1.05)	6.00 (0)
RPM	71.50 (8.48)	n/a
RPM during task	74.06 (11.80)	n/a

Table 5.2. Heart rate, ratings of perceived exertion, and revolutions per minute during experimental sessions. Data are means \pm standard deviation.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The purpose of this dissertation was two-fold. First, the literature on the effects of acute exercise and cognition was in need of a systematic review. The present state of knowledge about acute exercise and cognition did not allow researchers to make conclusions about the magnitude of the effect and the factors that influence it. A meta-analysis of the literature was performed to determine what cognitive changes occur during and following exercise and moderators that influence the relation.

After performing this systematic review, it became apparent that empirical studies on the effects of acute exercise on time estimation were needed. Human time estimation has been the subject of much empirical study but timing studies have been rarely performed with participants under a physical load. Thus, the second purpose of this dissertation was to focus on a critical aspect of cognitive performance, time estimation, and examine how it was influenced by acute exercise and caffeine. Several hypotheses were tendered which will now be discussed.

Hypotheses

First hypothesis. A meta-analytic review of the experimental literature on the effect of acute exercise on cognition would reveal a small, positive effect on cognitive performance. This effect was expected to be heterogeneous and moderated by characteristics of the participants studied, the exercise intensity and duration requirements placed on participants, and features of the research design. During exercise, participants' cognitive performance was impaired, $\Delta = -0.14$, whereas following exercise there was an improvement in cognitive task performance, $\Delta = 0.20$. Therefore, the mean overall effect of exercise on cognition was small but only positive

following exercise. The effect was heterogeneous and moderated by several variables, including the time at which cognitive tests were administered relative to exercise, exercise mode, type of cognitive task, and use of a resting control condition. These results are indicative of the complex relation between exercise and cognition. Cognitive performance may be enhanced or impaired depending on when it is measured, the type of cognitive task selected, and the type of exercise performed.

Second hypothesis. An experimental study of the effect of acute exercise on timing performance would reveal significant differences between rest and exercise conditions. Exercise was expected to speed up the participants' internal clock, increasing the subjective length of stimuli on a multiple-trial referenced temporal discrimination task (Penton-Voak et al., 1996). This would result in shorter-duration stimuli being identified as the standard, shifting the generalization gradient to the left. Furthermore, it was anticipated that exercise would offset the arousal-related lengthening of subjective estimates that occur towards the end of a testing session (Wearden, Pilkington, & Carter, 1999). As predicted, generalization gradients from a multiple-trial referenced task shifted to the left when performed during exercise. However, exercise did not prevent subjective lengthening as the task progressed.

Third hypothesis. Exercise was not expected to influence timing performance on an episodic temporal generalization task, because the durations to be discriminated are only held briefly in working memory and will be timed with the same clock speed (Wearden, 2008). This hypothesis was confirmed, as there were no differences in task performance resulting from exercise. Further, it has been proposed that arousal manipulations (e.g. drugs, stress) affect timing due to their influence on the internal clock component of the scalar timing model (Penton-Voak et al., 1996). It was unclear whether exercise-induced arousal would affect timing in a

similar manner or whether it would also influence the working memory component of the model. Exercise had no effect on measures of working memory (Random Number Generation, Operation Span) performed in temporal proximity to the scalar timing tasks, which provided evidence for the specificity of exercise-induced arousal on the internal clock.

Fourth hypothesis. A double blind experiment of the effects of caffeine administration on cognitive performance would reveal additive effects of exercise and caffeine on timing processes. Participants in the caffeine group and the exercise condition were expected to have the fastest internal clocks, and therefore identify shorter stimuli as the standard to a greater extent than participants in the other conditions. Visual inspection of the gradient for participants in the caffeine group and exercise condition revealed that it had the largest leftward shift. During rest, the gradient for the participants in the caffeine group shifted to the right and peaked at the comparison stimulus that was two steps longer than the standard. In terms of the scalar expectancy theory, this shift would result from a reference duration being timed with a faster clock because the standard would be associated with more pulses from the pacemaker. When the clock slowed down during the resting control condition, a greater number of pulses being associated with the standard resulted in longer stimuli being required for these pulses to elapse. This finding demonstrates the sensitivity of the internal clock to arousal manipulations such as acute exercise, rest, and caffeine.

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APPENDICES

APPENDIX A

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Discussion

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APPENDIX B

ADDITIONAL INFORMATION QUESTIONNAIRE
Date: _____

ADDITIONAL INFORMATION QUESTIONNAIRE

INSTRUCTIONS: The purpose of this questionnaire is to obtain additional information about you that might be relevant to this study. It is important that you answer each question honestly and completely. Please ask us if you need clarification about any of the questions. Put a question mark (?) next to any question you are not certain about.

- 1. _____ Have you ever had a head injury?
- 2. Do you play an instrument?
- 3. _____ Do you regularly drink coffee?
- 4. _____ Do you regularly drink tea?
- 5. _____ Do you regularly drink caffeinated soft drinks?
- 6. Please list ALL supplements that you use: (e.g. multivitamin, fish oil, etc)

7. Please list ALL over-the-counter medications that you use: (e.g. allergy medication, etc)

8. Please list ALL medications that you use that your doctor prescribes:

APPENDIX C

PHYSICAL ACTIVITY QUESTIONNAIRE

Date: _____

PHYSICAL ACTIVITY QUESTIONNAIRE

INSTRUCTIONS: The purpose of this questionnaire is to obtain information about your current physical activity and exercise habits that you perform regularly, at least once a week. Please answer as accurately as possible. Circle your answer or supply a specific number when asked.

1. For the last **three months**, which of the following moderate or vigorous activities have you performed **regularly**? (*Please circle YES for all that apply and NO if you do not perform the activity; provide an estimate of the amount of activity for all marked YES. Be as complete as possible.*)

Walking

NO	YES→	How many sessions per week? How many miles (or fractions) per session? Average duration per session?	(minutes)
Stair	r Climbin	ıg	
NO	YES→	How many flights of stairs do you climb UP each day? (1 flight = 10 steps)	
Jogg	ing or R	unning	
NO	YES→	How many sessions per week? How many miles (or fractions) per session? Average duration per session?	(minutes)
Trea	dmill		
NO	YES→	How many sessions per week? How many miles (or fractions) per session? Average duration per session? Speed?(mph) Grade(%)	(minutes)
Bicy	cling		
NO	YES→	How many sessions per week? How many miles per session? Average duration per session?	(minutes)
Swir	nming La	aps	
NO	YES→	How many sessions per week? How many miles per session? (880 yds = 0.5 miles) Average duration per session?	(minutes)

Aerobics/	/Calisthenic	s/Floor	Exercise
-----------	--------------	---------	----------

NO	YES→	How many sessions per week? Average duration per session?	(minutes)
Moc (e.g. Soci	lerate Sp volleyba al dancin	orts II, golf (not riding), g, doubles tennis)	
NO	YES→	How many sessions per week? Average duration per session?	(minutes)
Vige (e.g.	orous Rac Racquet	equet Sports ball, singles tennis)	
NO	YES→	How many sessions per week? Average duration per session?	(minutes)
Oth Or 1 Run	er Vigoro Exercise I ning (e.g.	ous Sports involving . Basketball, soccer)	
NO	YES→	How many sessions per week? Average duration per session?	(minutes)
Oth (e.g.	er Activit Yoga)	ies	
NO	YES→	Please specify: How many sessions per week? Average duration per session?	(minutes)
Wei (Ma	ght Train chines, fre	ing ee weights)	
NO	YES→	How many sessions per week? Average duration per session?	(minutes)

2. How many times a week do you engage in vigorous physical activity long enough to work up a sweat? ______ (*times per week*)

APPENDIX D

MEDICAL HISTORY QUESTIONNAIRE

MEDICAL HISTORY QUESTIONNAIRE

INSTRUCTIONS: The purpose of this questionnaire is to obtain in formation about your medical history. It is important that you answer each question honestly and completely in order to minimize the risks associated with you participation in this research. Please ask us if you need clarification about any of the questions. Put a question mark (?) next to any question you are not certain about.

- 1. _____ Does your mother or father have high blood pressure (i.e., hypertension)?
- 2. _____ Do you have, or have you ever had, any heart trouble?
- 3. _____ Do you frequently suffer from pains in your chest?
- 4. _____ Do you often feel faint or have spells of severe dizziness?
- 5. _____ Do you now have, or have you ever had, high blood pressure?
- 6. _____ Do you have a bone or joint problem, such as arthritis, that has been aggravated by exercise, or might be made worse with exercise?
- 7. Have you ever fainted during exercise?
- 8. _____ Has any member of your family died of a heart attack prior to the age of 50?
- 9. _____ Have you ever had a seizure?
- 10. _____ Do you regularly smoke cigarettes?
- 11. _____ Do you have any pain that you have been experiencing for more than a month?
- 12. _____ Were the results of your last medical exam normal?
- 13. _____ Is there a good physical reason not mentioned above why you should not engage in vigorous physical activity?

If so, describe it:

APPENDIX E

24-HOUR HISTORY QUESTIONNAIRE

Session Number: _____

Date: _____

24-HOUR HISTORY QUESTIONNAIRE

INSTRUCTIONS: The purpose of this questionnaire is to obtain information about the past 24 hours. We use this questionnaire to make sure that your arousal level and your fatigue have not been drastically modified prior to this session. It is i mportant that you an swer each question honestly and completely. P lease as k us if you need clarification about any of the questions.

1. When did you last have (and amount):

Coffee: _____

Tea :

Soft drink: _____

Alcohol: _____

2. What sort of physical activity did you perform yesterday?

3. What sort of physical activity have you performed today?

4. Describe your general feelings by checking **one** of the following:

excellent very good good neither good or bad bad very bad terrible

5. To the nearest half-hour, please indicate the amount of sleep you had last night.

hours Is that your normal amount? ______6. Starting with yesterday, please indicate the time you woke up, went to sleep, and any physical activity that you have done.

YESTERDAY			TODAY
Time	Activity	Time	Activity
5:00am		12:00am	
5:30am		12:30am	
6:00am		1:00am	
6:30am		1:30am	
7:00am		2:00am	
7:30am		2:30am	
8:00am		3:00am	
8:30am		3:30am	
9:00am		4:00am	
9:30am		4:30am	
10:00am		5:00am	
10:30am		5:30am	
11:00am		6:00am	
11:30am		6:30am	
12:00pm		7:00am	
12:30pm		7:30am	
1:00pm		8:00am	
1:30pm		8:30am	
2:00pm		9:00am	
2:30pm		9:30am	
3:00pm		10:00am	
3:30pm		10:30am	
4:00pm		11:00am	
4:30pm		11:30am	
5:00pm		12:00pm	
5:30pm		12:30pm	
6:00pm		1:00pm	
6:30pm		1:30pm	
7:00pm		2:00pm	
7:30pm		2:30pm	
8:00pm		3:00pm	
8:30pm		3:30pm	
9:00pm		4:00pm	
9:30pm		4:30pm	
10:00pm		5:00pm	
10:30pm		5:30pm	
11:00pm		6:00pm	
11:30pm		6:30pm	

APPENDIX E

CAFFEINE SENSIVITY QUESTIONNAIRE

Caffeine Sensitivity Questionnaire

Instructions: We are interested in knowing how sensitive you are to caffeine. Caffeine sensitivity refers to the degree to which you feel various physical or psychological symptoms in response to taking caffeine. Please answer as honestly and completely as you can.

1. The most common symptoms associated with caffeine consumption are feelings of anxiety or nervousness, muscle tension, shakiness or tremors and insomnia. If you have never experienced the above symptoms after taking a large amount of caffeine then you have below normal caffeine sensitivity. If you experience intense symptoms after taking caffeine then you have above normal caffeine sensitivity. Which of the following best describes you? (check one)

My sensitivity to caffeine is below normal

My sensitivity to caffeine is about normal_____

My sensitivity to caffeine is above normal

2. Have you ever used NoDoz or other caffeine pills?_____

If yes, did this elicit any negative side effects?_____

Explain_____

3. What is the greatest quantity of caffeine you have ever consumed in one day?_____

Did this quantity elicit any negative side effects?_____

Explain_____

4. Have you ever experienced negative side effects from caffeine?

Explain_____