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AN INVESTIGATION OF RPE-HEART RATE AND THE RPE-LACTATE RELATIONSHIPS IN ELITE ATHLETES

BY MARK A. STOOVÉ

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ABSTRACT

This thesis investigated the relationship of ratings of perceived exertion (RPE) with heart rate (HR) and blood lactate (La) that involved four studies. The first study concerned comparing RPE relationships with elite swimmers during exercise tests performed during in-season (IS) and off-season (OS) periods of training. Participants (males = 8, females = 4) performed incremental aerobic tests (7 x 200 m swim) six months apart during IS and OS training. RPE, HR, and La were measured upon completion of each swim stage, which were undertaken on 5-minute cycles. The relationships between RPE and physiological parameters were analysed by comparing HR-RPE and La-RPE ratios between IS and OS tests. ANOVAs (2 x 3 within-groups) were used to determine differences in RPE ratios at low workloads, the anaerobic threshold (AT), and at maximal workloads between tests performed during IS and OS training. Little difference was found in RPE ratios at the lowest workloads. At the AT and maximal exertion, however, athletes demonstrated greater HRs and Las for a given RPE during IS compared to OS training. Workload also affected RPE relationships independent of period of training. Decreases in HRs and increases in La concentrations at a given RPE were found as workloads increased. The results from this study showed that elite athletes were able to sustain greater levels of physiological activation for a given perceptual rating during IS compared to OS training.

The second study examined the effect of high ambient temperatures on the HR-RPE and La-RPE relationship in elite cyclists during self-paced cycle tests. Participants (*N* = 12) performed a 30-minute time trial (30TT) in moderate (23°C) and hot (32°C) ambient temperatures with RPE, HR, and La measured every five minutes throughout the tests. Tests were self-paced, and athletes were instructed to complete 30 minutes of cycling with the highest average power output possible. The relationships between RPE and physiological parameters were analysed using 2 x 3 within groups ANOVAs to compare

HR-RPE and La-RPE ratios between conditions at minute-10, minute-20, and minute-30 of the 30TTs. Results showed increases in RPEs during 30TTs performed in hot compared to moderate temperatures. RPEs were greater for a given HR during the second half of 30TTs performed in hot compared to moderate temperatures. Lower power outputs during tests performed in high temperatures resulted in reduced La concentrations during the latter half of the 30TTs performed in this condition. Incremental increases in RPE over the duration of the tests performed in both conditions resulted in lower La-RPE ratios at minute-20 and minute-30 in the hot temperature condition. The workload effects detected in Study 1 were found for the HR-RPE relationship in both conditions, and the La-RPE relationship in the moderate temperature condition. This study showed greater RPEs for a given physiological demand and power output during 30TTs performed in hot compared to moderate temperatures. This study also showed that the expected La-RPE relationship breaks down in elite athletes during a self-paced cycling protocol in high ambient temperatures.

The third study investigated the effect of acute simulated moderate altitude (1800 m) exposure on the HR-RPE and La-RPE relationship in highly trained cross-country skiers during incremental ski-striding treadmill tests. Participants ($N = 9$) performed graded exercise tests to exhaustion in simulated sea level and moderate altitude conditions with RPE, HR, and La measured upon completion of each stage. HR-RPE and La-RPE ratios at the lowest workload, the AT, and at 90% of maximal work time between altitude and sea level tests were analysed using 2 x 3 within-groups ANOVAs. Although ANOVA results and effect size calculations showed some effect of altitude on RPE relationships, plots of RPE with physiological parameters show equivocal results and only small differences in responses between conditions. The moderate, rather than high altitude condition presented in this study might not have sufficiently impeded exercise capacity to show differences in RPE relationships. Workload effects were consistent with Study 1 results.

The fourth study was concerned with RPE relationships during upper and lower body work with elite kayakers and elite cyclists. Kayakers (males = 5, females = 6) and cyclists (males = 5, females = 6) performed graded exercise tests (GXTs) to exhaustion on kayak and cycle ergometers, with RPE, HR, and La measured upon completion of each stage. Results were analysed using 2 x 3 mixed design ANOVAs to compare HR-RPE and La-RPE ratios at the lowest workloads, the AT, and at maximal effort between kayak and cycle groups. Results showed that kayak exercise resulted in greater HRs and La concentrations, and lower power outputs for a given RPE compared to cycle exercise. HR-RPE responses were not consistent with previous research findings, and this result was possibly affected by extremely high maximal La concentrations for kayakers and a diminished mediating role (compared to untrained individuals) of La on RPE for elite upper body trained participants. Workload effects agreed with those presented in Study 1 and Study 3. These results showed that HR-RPE and La-RPE relationships differed between kayak and cycle work performed by elite upper and lower body trained athletes. Greater levels of physiological activation for a given RPE were found during kayak work, despite kayakers performing at lower power outputs for a given RPE compared to cyclists.

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CHAPTER 1

INTRODUCTION

In the early 1960s Borg (1961) developed the first category scale for the measurement of perceived exertion, which later became known as the Borg, or Rating of Perceived Exertion (RPE) Scale (Noble & Robertson, 1996). In the years since, the RPE scale has become the standard measure of perceptions of exertion in a range of clinical, applied, and research settings. Perceived exertion can be defined as feelings associated with how strenuous a physical task is. Perceived exertion concerns subjective aspects of stimulus intensity and sensory and affective responses to physical activity (Borg, 1998). The early emphasis of research in RPE involved the physiological factors or conditions that influenced perceptions of effort. More recent investigations have shifted to the influence of psychological factors in the effort sense, the use of RPE in prescribing and monitoring exercise, and the clinical application of RPE in medical settings to monitor physiological and perceptual responses in disease states and during rehabilitation.

Much of the research involving RPE has been descriptive, with researchers exploring the relationships between RPE and physiological factors in an attempt to establish the physiological cues that influence the perception of exertion. Researchers have identified two major sets of cues, central and peripheral, involved in the perception of exertion (Pandolf, 1982). Peripheral cues relate to feelings of strain in the exercising muscles and joints, and central cues involve sensations associated with cardiopulmonary demand. Researchers in RPE have examined the integration of these physiological cues in mediating perceptions of exertion. Rather than identifying a single, overriding physiological mediator of perceptions of exertion, researchers have suggested that multiple physiological cues integrate into a gestalt to determine an overall perception of effort (Mihevic, 1981; Pandolf, 1983).

Although there is general agreement as to the variables that contribute to perceptions of effort, controversy remains regarding the relative contribution and the pattern of relations between physiological cues and RPE. Peripheral factors appear to dominate an individual's perception of effort at all work intensities (Borg & Noble, 1974; Watt & Grove, 1993). When aerobic demand is high, however, central signals may act as amplifiers to peripheral signals, and may actually dominate the effort sense above a certain intensity threshold (Cafarelli, 1977; Robertson et al., 1986). In order to establish the relative contribution of central and peripheral factors in determining perceptions of exertion, physiological cues and their relation to RPE have been examined. For example, HR appears to exhibit a linear relationship with RPE, with correlation coefficients for HR and RPE ranging between $r = .42$ and $r = .94$ across a range of tasks and exercise intensities (Noble & Robertson, 1996). Other researchers have demonstrated strong correlations for RPE and La ranging between $r = .79$ and $r = .98$ (Steed, Gaesser, & Weltman, 1994). Some researchers have reported, however, that La may only affect RPE once a critical exercise intensity has been reached (e.g., AT; Mihevic, 1981). A major criticism of these conclusions is that they mostly stem from descriptive studies where causality cannot be determined. Attempts to manipulate HR and La experimentally and monitor RPE responses have resulted in inconsistent findings (e.g., Allen & Pandolf, 1977; Pedersen & Welch, 1977).

Another limited aspect of RPE research is that it has largely ignored RPE relationships in elite level athletes. RPE relationships have usually been tested using relatively sedentary participants at submaximal exercise intensities. Recent evidence (Martin & Andersen, 2000; Martin, Andersen, & Lee, 1999) has suggested that, at the elite level, the relationship between RPE and some physiological cues of exertion may uncouple. Despite RPE becoming a common tool for monitoring the subjective responses of athletes during exercise testing, there remains little evidence concerning how RPE relates to physiological parameters in elite participants. Establishing a pattern of RPE responses in elite performers may be useful in monitoring training adaptations to ensure that athletes attain certain performance criteria while avoiding overtraining and fatigue. Further research is needed to establish the stability of RPE relationships in elite athletic performers so that athlete conditioning and well-being can be more accurately monitored.

Some researchers have suggested that variations in environmental conditions, such as temperature (Glass, Knowlton, & Becque, 1994) and altitude (Young, Cymerman, & Pandolf, 1982), may disturb the relationship between RPE and some physiological parameters. Again, this research has almost exclusively used non-elite performers and whether such relationship alterations occur in elite athletes remains unanswered. Elite athletes are sometimes required to perform or train under a variety of conditions (e.g., at altitude, in extreme temperatures). It is important, therefore, to establish how the relationship between RPE and physiological parameters in elite athletes are affected by environmental conditions. Factors, such as the types of muscle groups used during exercise (Pivarnik, Grafner, & Elkins, 1988) and the level of fitness of participants (Haskvitz, Seip, Weltman, Rogol, & Weltman, 1992), may also distort RPE relationships. The influence of training state, temperature, altitude, and working muscle groups on RPE relationships in elite performers may provide valuable information to assist in monitoring the fitness and well-being of athletes.

This study used archival data collected by the Australian Institute of Sport (AIS) to examine RPE relationships in elite, world-class athletes. These data have been collected using standardised testing protocols that are employed regularly to monitor the fitness and training adaptations of elite athletes. The data consist of RPE, La, and HR responses to GXTs and time trials of athletes from different sports under a variety of conditions. GXT and 30TT responses were compared between: (a) swimmers during pre-competition and off-season training, (b) cyclists tested in hot and moderate environmental temperatures, (c) cross-country skiers tested in simulated altitude and sea-level conditions, and (d) athletes who compete in sports where different muscle groups predominate (i.e., cyclists and kayakers).

Investigative Rationale

The investigative basis of the studies presented in this thesis centres around the paucity of published research examining RPE relationships in elite athletes. In addition, few studies have examined these relationships across conditions commonly used to test training adaptations in elite performers (e.g., high ambient temperatures), or between different groups of elite athletes (e.g., sports using predominantly upper and lower body physiology). Such investigations are warranted given that RPE is being increasingly used to monitor elite athletes during training, and recent evidence suggests that elite athletes may process sensory information during physical work differently compared to sub-elite or sedentary participants (Martin & Andersen, 2000; Martin, Andersen, & Lee, 1999). The investigation of RPE relationships in elite athletes may offer important information for monitoring overtraining, athlete conditioning, and well-being. Although the research findings presented in this thesis are not intended to establish definitively the characteristics of the relationships of RPE with HR and La in elite athletes, the results can be used as a basis for future investigations in this area.

The results from this thesis will explicitly examine the *relationship* of RPE with HR and La by examining ratios between RPE and these physiological variables. Much of the RPE literature purports to investigate these associations by separately relating perceptual and physiological parameters with workloads or exercise intensities, and then presenting findings in terms of the relationship between RPE and physiological mediators of exertion. Yet this method of analysis does not adequately describe how perceptual and physiological parameters change in relation to each other during exercise. The analysis of ratios between RPE and physiological parameters can potentially detect subtle changes in these variables over time and between experimental conditions that might not be apparent when describing these variables separately.

By exploring RPE, HR, and La relationships using ratios, the results from this thesis aim to more explicitly target the characteristics of the association between perceived exertion and physiological responses in elite athletes. Such analyses have recently been shown to offer potentially valuable information regarding the training status and performance capabilities of elite athletes (Martin & Andersen, 2000). Ratios between RPE and physiological variables are likely to be particularly sensitive to change. Such sensitivity may be useful in the context of elite athletic performance where small changes in exercise physiology, the processing of sensations of exertion, and performance can have significant consequences (e.g., the difference between a gold medal and not making the final). The results presented in this thesis are described both in terms of statistical significance and effect size in order to be sensitive to nonsignificant but potentially important alterations in RPE relationships.

Collection and Release of Archival Data

The studies presented in this thesis used archival data collected by physiologists at the AIS. The data were supplied with the permission of the head of the physiology department, Dr Alan Hahn, and senior physiologists involved in the collection of the data, Dr. David Martin and Dr David Pyne. These data were not collected to explicitly examine the relationship between RPE and physiological responses, rather they were routinely collected to monitor the fitness and training adaptations of athletes training at the AIS. Because of this, standard informed consent protocols were not followed regarding the collection and release of this data. Instead, the doctoral candidate received permission to examine the data from a number of senior physiologists who were involved in their collection. Names and other personal identifying information were removed from data sets prior to their release. The candidate and supervisor of this PhD had worked previously with the physiologists at the AIS on a number of projects and expressed interest in the data sets used in this thesis. The data were released to the doctoral candidate because they were lying fallow in the archives of the AIS and were unlikely to be analysed by staff.

CHAPTER 2

LITERATURE REVIEW

Introduction

Perceptions of exertion are made often during physical activity as individuals continually process sensory and external cues and make judgements about how hard they are working. These judgements involve the subjective interpretation of stimuli and provide an indication of how individuals cope with their internal conditions and the external demands of the environment. The subjective assessment of physical functioning in certain situations means that the physical perceptions of individuals, or the demands of particular tasks, can be studied psychologically. Measuring perceived exertion provides valuable information about how healthy people adapt to strenuous work and how people who are ill perceive their ability to adapt to disease and rehabilitation. A decrease in work capacity perceived by an individual might be a reason to seek medical help. Conversely, an increase in work capacity not perceived by an individual as more strenuous might be an indicator of improved physical fitness. Measuring perceived exertion provides an important indication of safe or beneficial levels of physical activity and can alert people to the detrimental effects of either too much or too little physical work. RPE has been used in a variety of areas, such as the post-operative monitoring of an individual during rehabilitation and the physical and environmental demands of occupational tasks. RPE has also been used to determine optimal exercise training workloads and to monitor exercise testing and prescription.

RPE, like most other constructs in perception, has historically undergone an evolution in terms of definitions, conceptual frameworks, and applied models. In this chapter I will briefly describe perceived exertion in the context of the broader area of psychophysics. The measurement of perceived exertion will be explored, along with the development of the RPE scale. The relationship of RPE to physiological cues of exertion will be examined, together with attempts to integrate these relationships into RPE models. The effect physical training has on the relationship between RPE and physiological variables will be discussed, along with the effects of different environmental conditions on RPE. The use of RPE in monitoring elite level training will be reviewed, and investigations concerning RPE relationships in elite level athletes will be discussed. This chapter concludes with a discussion of statistical and research design concerns in the RPE literature and a statement of the purpose of the research reported in this thesis.

Psychophysics and the Measurement of Perception

Perceived exertion is part of the broader area of psychophysics that deals with individuals' perceptions of the physical world. Psychophysics concerns the study of human perception, and specifically relates to quantifying the relationship between physical stimuli and perceptual responses (Gescheider, 1976), for example, the relationship between the frequency of breathing (physical stimulus) and perception of exertion (perceptual responses).

Psychophysics was pioneered by German physiologist Ernst Weber (1795-1878). Weber was concerned with reconciling the apparent difference between the physical world and psychological interpretations of that world. He believed that human perception could be described in terms of psychological laws that could be used to predict and measure perceptual responses (Noble & Robertson, 1996). A concept fundamental to Weber's work, and the future development of psychophysical laws, was the difference threshold. The difference threshold is the smallest detectable difference between two stimuli. The difference threshold is typically (although not always) described in terms of a just noticeable difference, that is, the amount of change in a stimulus required for a difference to be detected (Geissler, 1990).

In 1834 Weber found that the amount of change in a stimulus required to detect a just noticeable difference was directly proportional to the magnitude of the stimulus. A smaller change in stimulus was required to produce a just noticeable difference when the absolute magnitude of the stimulus was also small. As intensity of stimulus increases, so too does the differential threshold, and proportionally so. Although Weber himself did not organise his observations into a precise formula, Fechner (1860/1961) used Weber's work to construct Weber's Law.

$$\triangle I / I = k$$

Where I is the stimulus intensity, $\triangle I$ is the change in intensity necessary for a just noticeable difference, and k is the resultant constant that varies according to the sensory system or type of stimulus being measured (for a review see Blackwell, 1974).

Fechner (1860/1961) extended on the work of Weber and proposed that the just noticeable difference could be used as a standard unit to measure the subjective magnitude of sensation. Fechner worked from the premise that, for a given sensory system, all just noticeable differences represent equal units of sensation, with a particular sensory modality, regardless of the absolute intensity of the stimulus (Geissler, 1990). The relationship, known as Fechner's Law (1860/1961), follows a logarithmic pattern over the full stimulus intensity range.

$$S = k \log I$$

Where S is the magnitude of sensation, log I is the logarithm of the intensity of stimulus, and k is the constant from Weber's Law for a specific sensory dimension (for a review see Schiffman, 2000).

Weber's Law has been shown to hold reasonably true for a range of stimuli (although it tends to breakdown at extremely weak or extremely strong intensities) and sensory modalities. Fechner's Law and the contention of equal just noticeable differences across a full range of stimuli, however, does not fit as well, especially with sensory systems that often have to extend an enormous range of stimulus intensity with neural units of limited ability (e.g., Scharf & Buus, 1986).

The psychophysical methods used by Weber and Fechner were indirect methods, in that the perceptual responses were extrapolated from the measurement of the stimulus. Because of the inter-subjectivity of perception, direct measurements of subjective reality were considered difficult or unimportant (Marks, 1974). Stevens challenged this assumption (Stevens, 1935; Stevens & Davis, 1938), and believed that more direct methods of measuring sensation could be used, where assessments were made directly from the sensation themselves.

The most frequently used direct method of measuring sensation was magnitude estimation. Magnitude estimation involves an individual being presented first with a standard stimulus and then presented with a series of randomly ordered stimuli to which they assign a number that expresses the magnitude of the stimuli in relation to the standard stimulus (Geissler, 1990). Such methods are also called ratio methods, because individuals are asked to identify the magnitude of a stimulus as a ratio of a standard stimulus. Using direct methods of measuring sensation such as magnitude estimation, Stevens and other modern psychophysicists, found that sensation grows as a power function of the stimulus.

Steven's power law states that the sensory experience is a power function of stimulus intensity, and is expressed as:

$$S = kI^b$$

Where S is the magnitude of sensation, k is a constant that accounts for the units of measurement for a sensory dimension, I is the stimulus intensity, and b is the power exponent to which the intensity is raised. The b exponent directly describes the relation between sensory and stimulus magnitude, with each sensory dimension having a different exponent.

Richardson and Ross (1930) were the first to use magnitude estimation to measure sensory perception, showing directly that the perception of loudness grows as a function of sound pressure. Subsequent research (Stevens, 1936) confirmed this finding and Steven's power law has been validated using many different sensations (e.g., brightness, smell, taste, the length of lines), each with its own exponent describing the extent to which sensory magnitude changes with stimulus magnitude.

Perceived Exertion

Perceived exertion can be defined as the detection and interpretation of sensations arising from the body during physical activity (Noble & Robertson, 1996). Borg (1998) stated that common sense and experience helped define the content and meaning of perceived exertion, with feelings associated with effort, breathlessness, fatigue, and aches in working muscles used to describe the concept. Classical psychophysics has largely dealt with the interpretation of single stimuli through one sensory system (e.g., the brightness of light, the loudness of sound). The concept of perceived exertion is different, however, in that it involves the interpretation of multiple stimuli to form an overall perception of physical exertion. The total perception of exertion is an integration of multiple physical sensations with psychological factors, such as motivation and the past experiences of individuals. Multiple cues, such as heavy breathing, muscular pain, sweating, and fatigue, are processed to determine an overall perception of exertion. The gestalt of physiological and psychological contributors to RPE and the integration of multiple physiological systems in fulfilling exercise demands have made it difficult for researchers to make causal inferences between individual physiological cues and RPE. According to Borg (1998), physiological variables, such as La and HR, should be looked upon as simply correlates of RPE.

The Development of the Borg RPE Scale

As discussed briefly in a previous section, ratio scaling methods, such as magnitude estimation, have become popular with modern psychophysicists. Although this method is effective for intraindividual comparison and the development of general psychophysical functions, ratio scaling is not helpful in determining perceptual differences between individuals because individuals must make comparisons relative to a standard stimulus (Borg, 1982). For example, an individual presented with a standard stimulus of running at 5 $km.h^{-1}$ may rate the perception of physical exertion as "10." Based on this standard, they subsequently rate running at 10 $km.h^{-1}$ as "15." Another person, however, who rates 5 $km.h^{-1}$ as "7" may then rate 10 $km.h^{-1}$ as "12." Yet this person may not perceive any more physical strain than the person who rates this intensity as "15." The difference in their perceptual ratings is based on the absolute numbers individuals choose for the standard stimulus, not on the perceptual intensity that is evaluated. In response to these and other problems associated with interindividual comparisons using ratio scales, rating methods were developed, where individuals separate stimuli into categories according to intensity and assign a number to the stimuli.

The concept of perceived exertion was first introduced in the late 1950s, and was followed soon after by methods for measuring perceived exertion, fatigue, and breathlessness. Early work on perceived exertion used measures of magnitude estimation to monitor subjective responses to short-term (less than one minute) work on a bicycle ergometer. Borg and Dahlstrom (1960) found that perceived pedal resistance followed a positive accelerating function with work, with an exponent of 1.6. Borg and colleagues later found similar positive accelerating functions using a range of ratio scaling methods and various modes of exercise of both short and longer (several minutes) duration (Borg, 1962). Although these studies were able to establish the rate at which subjective perceptions of exertion increased with work load, as stated above, using ratio scaling methods to measure perceptual responses provided no avenue for interindividual comparisons. Because exercise and sport scientists are often concerned with measuring interindividual differences, a rating method for measuring subjective responses to exercise intensity was needed.

The underlying premise behind the development of a rating scale for perceived exertion was that the perceptive range can be set equal for all individuals. The bottom of the perceptive range is constant because the point where no exertion is sensed is the same for all individuals. The top end of the perceptive range is also constant, as maximum exertion is the same for all individuals regardless of the workload at which this maximum intensity occurs. Disregarding the physical fitness of the participants, the different performance ranges, the modes of exercise, or the conditions under which exercise is performed, the range between no perceptual response and maximum perceptual response is equal for all individuals. For a review of theory on perceptive range see Borg (2001).

Throughout the development of the RPE scale, Borg highlighted the importance of aligning RPE with HR. Borg considered HR to be a good indicator of physical strain because HR exhibits strong linear correlations with workload. Borg reasoned that if the RPE scale was also a good indicator of physical strain, then RPE should increase linearly with HR and workload. Early development of the RPE scale resulted in a 21-point scale that correlated between .80 and .90 with HR (Borg, 1961). Despite these strong correlations, Borg (1970) made some modifications to the scale so that changes in RPE more closely followed changes in HR. The aim of these modifications was based on the premise that HR would approximate 10 times the RPE value. The new 15-point scale (ranging from 6 to 20) used modified verbal anchors and, because a low resting HR for many adults is close to 60, the number 6 was chosen as a starting point. This 15-point scale became known as the Borg, or RPE scale, and has since become the standard for measurement of perceptual responses to physical strain. Borg (1985) made slight modifications to the RPE scale to improve the precision of the verbal anchors and again increase the linearity between RPE and workload (see *Figure 2.1*). Despite the use of HR as a physiological marker for the development of the RPE scale, research findings have since demonstrated a wide range of correlations between RPE and HR (r = .42 to .94) under a variety of conditions (Noble & Robertson, 1996). These results suggest that different conditions may perturb the relationship between RPE and HR, and that RPE is likely to be based on a complex integration of a number of physiological cues, and not primarily HR.

6	No exertion at all
7	
	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 2.1. The Borg RPE Scale (1985).

Borg was able to achieve linearity between the RPE scale and HR through the careful development of verbal categories associated with perceptions of exertion. The values assigned to responses on the perceptual scale was dependent upon the number of categories in the scale and the semantics used to anchor each category. When developing category scales, Borg selected well-defined terms that had comparatively constant meanings between different individuals. The RPE scale was developed to measure the intensity of perceived exertion in a universally agreed way, based on common experiences and judgements from many healthy people and patients (Borg, 1998). Borg was able to demonstrate constant interindividual meaning for particular expressions by examining the values people associated with different verbal descriptions of physical strain. Each verbal description received a mean rating and a standard deviation. Descriptions were then selected where quantitative scores did not overlap, and mean scores represented approximately equal intervals between descriptions. When there was little overlap in normal curves depicting the scores associated with different expressions, then different individuals would not likely confuse the numeric value relating to each expression. Borg argued that if there was a set interval between the mean scores associated with each expression, then the scale should satisfy the criterion of an interval scale.

Reliability and validity. Researchers have questioned the reliability of subjective ratings because, by definition, subjectivity implies something that is uncertain, variable, and based on individual perceptions (Stevens, 1971). Borg argued, however, that RPE is easy to describe over a large range of intensities, is a fairly concrete concept, and has many cues that vary according to exercise intensity and workload from which individuals can base their subjective perceptions of exertion. Borg further suggested that in no other area of psychology does the measurement of perception correlate with so many relevant physiological parameters (Borg, 1998).

Reliability of the RPE scale has been established using many different procedures. Borg and Ohlsson (1975) instructed participants to run 800 metres at three different speeds and correlations were calculated between HRs and RPEs. Intercorrelations for HRs and RPEs were similar between the first and second run (HR $r = .74$; RPE $r = .75$), the first and third run (HR $r = .64$; RPE $r = .69$), and the second and third run (HR $r = .89$; RPE $r = .87$). Strong correlations for HRs ($r = .87$) and RPEs ($r = .91$) were also found between two 1,200 m runs at different speeds. Reliability has also been established between treadmill and outdoor track running (Ceci & Hassmén, 1991). Borg, Karlsson, and Ekelund (1977) tested 20 male participants on a bicycle ergometer with two different protocols. One test asked participants to use HR to guide their intensity and the other asked them to use RPE to guide their intensity. The correlation between workloads associated with an RPE of 17 was .89 between the two tests.

Comparisons between HR and RPE have been regarded as assessing parallel test reliability (i.e., calculating correlations between tests that purport to measure the same concept). Strong correlations between HR and RPE have been reported irrespective of fitness, body size, or ergometer type (Bar Or, Skinner, Buskirk, & Borg, 1972; Skinner, Borg, & Buskirk, 1969). High correlations (r = .65 to .87) have also been reported between HR and RPE using arm and leg exercises (Sargeant & Davies, 1973). In addition, parallel test reliability has been established by strong correlations between RPE and other subjective tests of perceived exertion (r = .92 to .94; Borg, 1973; Borg, 1974).

Concurrent validity of the RPE scale is supported by the associations between RPE and HR reported above, and by associations between RPE and other physiological indicators of physical strain. Noble, Metz, Pandolf, and Cafarelli (1973) reported that ventilation (V_E) and respiratory rate (RR) accounted for large amounts of variance in RPE (R^2 = .23 to .55). Miyashita, Onodera, and Tabata (1986) tested groups of Japanese men and reported strong correlations between RPE and percentage of maximal HR (r = .84) and RPE and percentage of VO_2max (r = .76). In addition, Edwards, Melcher, Hesser, Wigertz, and Ekelund (1972) reported strong correlations during intermittent and continuous exercise for RPE and average power output (r = .97 and .94), oxygen intake (r = .97 and .92), HR

(r = .87 and .86), RR (r = .67 and .40), V_E (r = .94 and .90), and La (r = .77 and .63), all respectively.

The content and construct validity of the RPE scale was established during the development of the scale. As discussed earlier in this section, this development was based around the selection of easy to understand semantic anchors and carefully developed scale administration instructions.

Development of the RPE scale to be sensitive to markers of physiological exertion helped to establish the construct validity for the scale. The construction of the scale resulted in ratings of exertion increasing linearly with increases in exercise intensity (Borg, 1977) and HR (Borg, 1972). The assumption that an individual's perceptual range is constant, allowing for interindividual comparisons in RPE, also helped support the construct validity of the RPE scale. Perception of exertion should vary according to the relative physiological demands placed on an individual. According to the range model, measures such as absolute exercise intensity and HR should correlate well with RPE, but not as well as measurements corrected for an individual's work capacity (Borg, 1998). Ekblom and Goldbarg (1971) reported that after training, and in parallel to decreases in HRs at submaximal workloads, RPE was lower at a given level of oxygen consumption, but remained stable when related to oxygen consumption relative to maximum oxygen uptake. Further support for the construct validity of the RPE scale was provided by researchers who reported similar RPEs at fixed blood lactate concentrations (FBLCs) regardless of the exercise capacity of participants (DeMello, Cureton, Boineau, & Singh, 1987; Foster, Fitzgerald, & Spatz, 1999; Haskvitz, et al., 1992).

Perceived exertion measured using the RPE scale has also been found to predict performance, offering support for the predictive validity of the scale. Borg (1966, as cited in Borg, 2001) tested 90 army conscripts on a bicycle ergometer at a constant load of 230 W for 12 minutes with subsequent increases in workload of 33 W every 6 minutes until voluntary exhaustion. Participants rated their perceived exertion after the first minute and then every two minutes. As a measure of physical working capacity, time to exhaustion was moderately correlated with submaximal ratings of perceived exertion taken at minute-1 (r = -.56), minute-3 (r = -.72), and minute-7 (r = -.66). Robertson and Noble (1996) argued that, because RPE provides the same information about an individual's functional tolerance as physiological indicators, it is as valid as any physiological variable in predicting exercise performance. Some researchers have suggested that RPE ratings, relative to La levels, may be predictive of overtraining (Snyder, Jeukendrup, Hesselink, Kuipers, & Foster, 1993), and that HR-RPE ratios may be predictive of performance response to taper in elite cyclists (Martin & Andersen, 2000). For a review of the reliability and validity of the RPE scale, see Borg (1998).

The Development of the Borg Category Ratio Scale (CR-10)

Borg (1973) suggested that the properties of the RPE scale (e.g., linear relationships between RPE and workload and HR) made it suitable for use in most cases. When the purpose of investigation, however, is to study how perceived exertion grows as a function of physical intensity, or when investigators want to compare such functions between different exercise modalities, a ratio scaling method, such as magnitude estimation, is preferred. Ratio scaling is also more useful when examining physiological variables that do not grow linearly with workload, such as La accumulation and V_E (Noble & Robertson, 1996). Although ratio scaling is preferred when describing a psychophysical stimulus-response function, as reported earlier, ratio scaling has disadvantages when making interindividual comparisons.

By matching the linear relationship between the RPE scale and workload with the power function exponent of 1.6 for ratio measures of perceived exertion and workload, Borg constructed the first category scale with ratio properties for perceived exertion (Borg, 1973). This 20-point scale ranged between 0, no exertion, and 20, maximal exertion.

Tested with transient work of less than one minute, the scale produced an exponent of 1.6 with workload, although some participants did not to use the top of the scale. Aiming to simplify the scale, Borg (1982) produced a new category-ratio scale on a 10-point scale ranging form 0 to 10. In order to accommodate a rating of 1, "very, very weak" on the 20-point scale, into the 10-point scale, a half point (0.5) was created. Other verbal expressions were adopted from experiments with the 20-point scale, and the top of the scale was anchored with 10, "extremely strong (almost max.)." Maximal exertion was placed outside the top of the scale to reduce the tendency to not use the highest number.

Borg (1982) demonstrated the ratio properties of the CR-10 scale by randomly presenting five 30-second workloads to a group of 12 women. The data closely followed the expected power function of 1.6 between perceptions of exertion and workload. Interindividual perceived exertion comparisons were also made with 32 senior high school boys performing incremental exercise with six-minute durations. General increases in perceived exertion matched previously obtained power exponents. Individual CR-10 ratings closely correlated with HRs ($r = .88$), and were about equal with many previous studies with the category RPE scale.

Other researchers have since demonstrated the reliability of the CR-10 scale by comparing responses with other scales and with mediators of exertion. Ljunggren and Johansson (1988) examined participant responses on the CR-10 scale during bicycle ergometer work and found good split-half correlations (Spearman-Brown) with RPE ($r = .96$), ratings of pain ($r = .96$), HR ($r = .97$), and La ($r = .98$). Repeated-measures correlations were also strong. Harms-Ringdahl et al. (1986) compared responses on the CR-10 scale with a Visual Analog Scale, which had previously shown to be a reliable tool for the assessment of strain and pain. Pain was elicited in healthy participants by stressing joint structures at the elbow. Participants were asked to rate their pain on the CR-10 and the Visual Analog Scale in different sessions on different days with the scales presented in random order. Results showed a strong correlation between the two scales (*r* = .90).

Noble, Borg, Ceci, Jacobs, and Kaiser (1983) demonstrated the construct validity of the CR-10 scale by using the scale to measure leg effort, chest effort, and leg pain during bicycle ergometer work. These variables all showed similar positive accelerating functions with workload, resulting in exponents of between 1.63 and 1.67. Borg, van den Burg, Hassmén, Kaijser, and Tanaka (1987) examined relationships between RPE, HR, La, and CR-10 scores with workloads across cycling, running, and walking exercise tests. Exponents calculated to describe the relationship between exercise intensity and CR-10, RPE, HR, and La responses varied together, so that when the mode of exercise changed, all exponents changed proportionally. Concurrent validity was also demonstrated by correlating CR-10 scores with HR (Ljunggren, 1985; Marks, Borg, & Ljunggren, 1983). For a review of the reliability and validity of the CR-10 scale, see Borg (1998).

Perceptual Cues in the Effort Sense and the Physiological Mediators of RPE

Integral to the measurement of exertion is the assumption that perceptions associated with physical exercise have a physiological basis. The perception of effort involves a connection between external stimuli and internal physiological responses to those stimuli. The link between stimulus and physiology is important in providing feedback regarding exercise performance. Sensory feedback from physiological processes allows individuals to assess the quantity and quality of their performance and, if necessary, make adjustments to their exercise intensity to meet metabolic and task demands (Noble & Robertson, 1996).

Exercise physiology researchers have identified a multitude of variables associated with increased exercise intensity. Many of these variables are integrated to limit performance capacity. The conversion of substrates to produce energy often requires the presence of oxygen. Delivery of oxygen to the working muscles is limited by the efficiency of the cardiorespiratory system. The intra and extracellular environments limit the conversion of substrates for energy. High levels of La in the blood and low pH levels limit the chemical reactions that produce energy. The efficiency of the metabolism to remove La from working muscles depends in part, on cardiorespiratory functioning. These processes help individuals meet performance demands, and related variables (e.g., La, V_E) elicit sensations associated with increased exercise intensity. In the same way that physiological responses combine to limit exercise performance, the sensations associated with these responses also combine to create an overall perception of effort. The search for a primary cue for RPE is, therefore, a somewhat simplistic approach to a complicated physiological and perceptual process (Mihevic, 1981). As Borg (1962) noted in his early work, the overall perception of exertion is based on a gestalt of integrated perceptual cues. In addition, Noble et al. (1973) suggested that RPE measures a general response produced from a summation of metabolic, respiratory, cardiovascular, and endocrine responses.

Researchers have suggested that unless a cue can be consciously monitored during exercise it cannot act as potent sensory information for the perception of effort (Edwards et al., 1972). For example, Pandolf, Cafarelli, Noble, and Metz (1972) and Ekblom and Goldbarg (1971) demonstrated that participants do not actually perceive HR as a basis for their perceived exertion. Noble et al. (1973) suggested that, although not all physiological processes are attended to when exercising, the sensations that result from physiological processes are used to determine perceived exertion. For example, during exercise people do not attend to their increased HR per se, but do attend to processes associated with increased HR, such as increased V_E. Similarly, people do not consciously monitor La concentrations, but do attend to the feelings of muscular pain and fatigue that accompany high La levels.

Early work by Borg (1961) suggested that perceptions of effort were dependent upon input from muscles and from the circulatory system. Ekblom and Goldbarg (1971), however, were the first researchers to propose formally a two-factor model of perceived exertion that included local and peripheral sensory cues. In research designed to assess the contribution of physiological cues to RPE in different experimentally manipulated conditions, the authors found that RPE was higher at a given submaximal HR during cycling than during running. They attributed this finding to higher La levels that increased feelings of muscular strain during cycling. The authors proposed that RPE is primarily governed by local factors, especially when work involves limited muscle groups. Acknowledging the multiple and complex factors that influence RPE, Ekblom and Goldbarg added that when more muscle groups are used, V_E and circulation provide additional cues for perceived exertion beyond local factors.

Pandolf, Burse, and Goldman (1975) and Kinsman and Weiser (1976) developed models of perceived exertion that included both local and central factors and clusters of symptoms that related to each. These models describe levels of sensory processing that emanate from underlying physiological mediators and extend to perceptions of exertion. The Kinsman and Weiser model (see *Figure 2.2*) helped to clarify the conceptual framework of a multi-factor model of perceived exertion by linking each level of sensory processing back to clusters of underlying physiological mediators. The base of the model contains the physiological substrata that are made up of physiological processes that mediate subjective interpretations of exertion. The subjective interpretation of these physiological processes starts with discrete symptoms. This level contains a range of experiences, such as shortness of breath, aching muscles, and HR that have their origin in underlying physiological mechanisms. Discrete symptoms are then clustered at the "subordinate" level of sensory processing to make up specific symptoms of fatigue (i.e., cardio-pulmonary, general, local muscular). Subordinate clusters of fatigue symptoms are then combined to form a primary symptom cluster associated with the specific mode of exercise (e.g., cycling fatigue) at the "ordinate" level. Discrete symptoms are also combined at the ordinate level to mediate motivation and task aversion. At the top of the sensory processing model is "undifferentiated exertion," representing the "superordinate" level. At this level the primary symptom clusters are combined into a global and undifferentiated perception of exertion. At any level of the model, exertional symptoms can be traced back to the sensory pathway from which they developed.

In an early review of differentiated cues for perceived exertion, Pandolf (1978) advocated studying exertional symptomatology singularly to assess whether certain cues were primary or secondary influences on perceived exertion. In a later review, Mihevic (1981) suggested that the complexity of physiological processes involved in the perception of effort dictate that sensory cues should be examined simultaneously to assess their relative importance in determining perceptions of effort. In the most recent comprehensive text on perceived exertion, Noble and Robertson (1996) reported that peripheral signals appear to dominate perceptions of exertion at all exercise intensities, whereas central cues act as amplifiers to these signals when exercise progresses beyond a certain point (e.g., ventilatory threshold). In most circumstances, peripheral signals are transmitted as soon as a bout of exercise has begun and continue throughout. Cafarelli (1977) suggested that during cycle ergometer testing, central cues are not sensed until 30 seconds after commencing exercise, reflecting the time taken for acute cardiorespiratory adaptation to increased energy demands. Cafarelli concluded that perceptions of exertion experienced in the first 30 seconds of exercise were entirely peripheral and relied completely on the force of muscular contraction. Other researchers have reported that central signals of exertion may be dominant under particular circumstances, for example, when exercise is performed under hypoxic conditions (Young et al., 1982) or when forced breathing patterns are necessary (e.g., swimming; Noble, Kraemer, Allen, Plank, & Woodard, 1986).

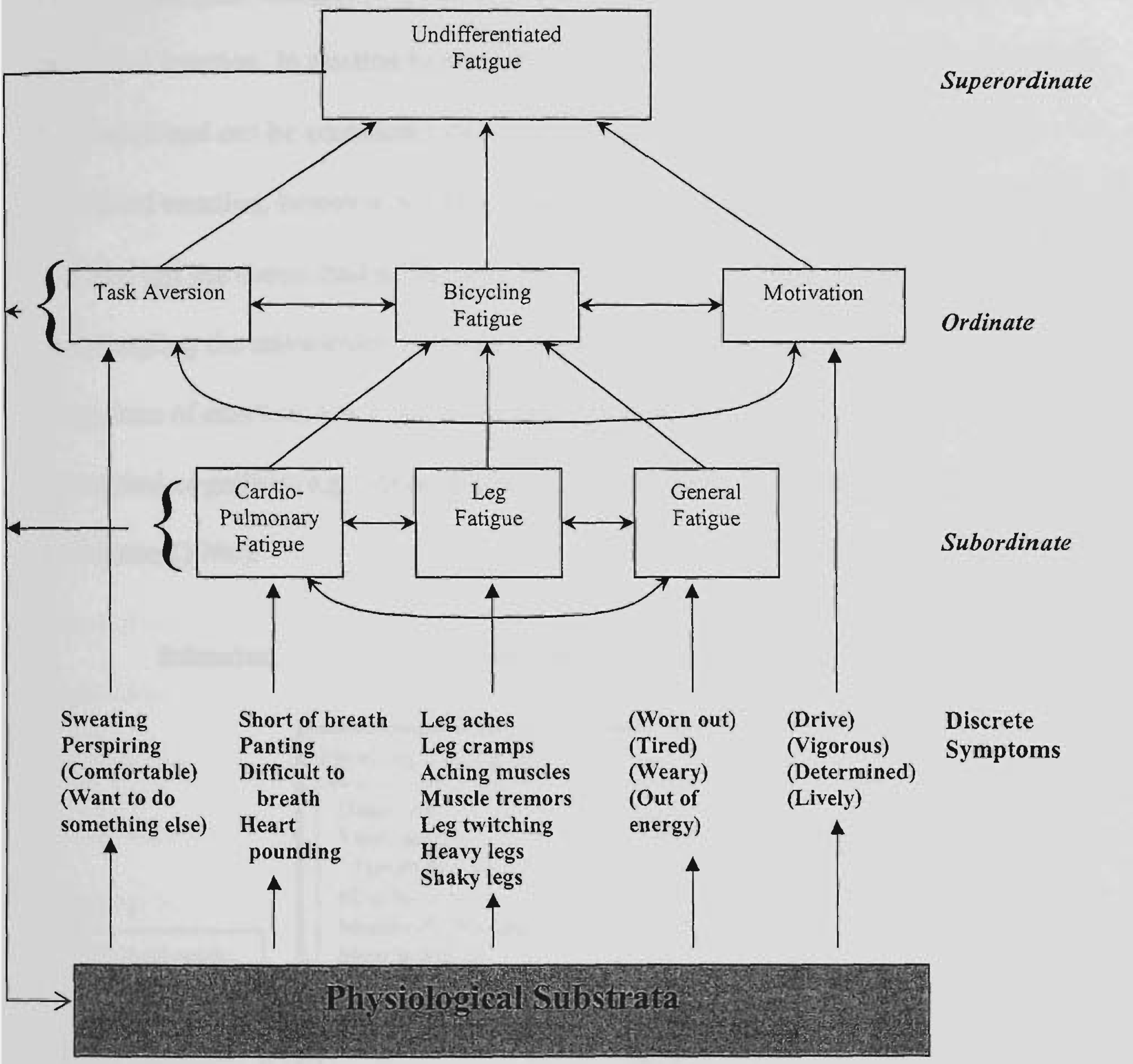

Figure 2.2. Pyramidal schema for subjective symptomatology during exercise using legs as an example (Kinsman & Weiser, 1975).

A more recent model to explain the relation between physical work and perceived exertion was presented by Hassmén (1991; see *Figure 2.3*). This model contains many of the discrete physiological symptoms identified in the Kinsman and Weiser (1975) model but also emphasises potential modifiers of the relation between discrete symptoms and perceptual responses of physical work. Nonspecific modifiers such as age, gender and training status are considered, along with a host of psychological mediators such as personality, task aversion, and motivation. The Hassmén model also deliberately avoids the term "fatigue." Borg (1986) makes explicit the distinction between fatigue and perceived exertion. In relation to physical exercise, Borg states that fatigue results *from* hard work and can be considered more to occur after exercise than during exercise. Perceived exertion, however, is more sensations that occur during exercise. These two models, and the conceptual differences between them, underline the complexities involved in untangling the relationship between physical work, physiological symptoms, and sensations of exertion. For a review of physiological (e.g., Kinsman & Weiser, 1975) and perceptual-cognitive (e.g., Hassmén, 1991) model of perceived exertion see Noble and Robertson (1996).

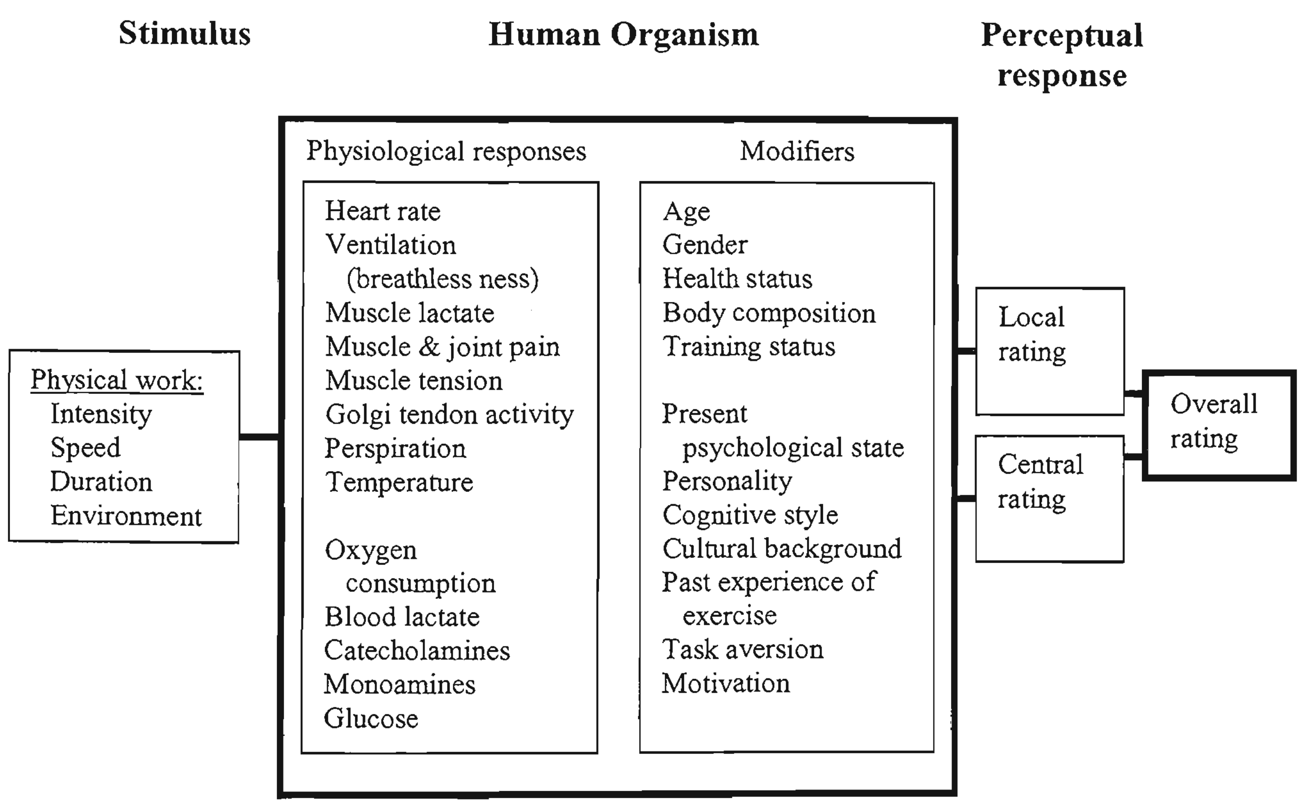

Figure 2.3. An explanatory model of the relation between physical work, and the physiological repsonses-psychological modifiers that are responsible for influencing the ratings of perceived exertion (Hassmén, 1991).

One potential reason for the inconsistencies in findings regarding the relationship between physiological parameters and RPE is the mediating influence of psychological factors (Morgan, 1973). Morgan suggested that personality type might mediate RPE and reported that extroverts rated the same work load as lighter than introverts. Robertson, Gillespie, Hiatt, and Rose (1977) found that sensory augmenters consistently rated the same workloads as more intense compared to participants classified as sensory reducers. It has also been suggested that perceived exertion ratings might be influenced by motivation, either to perform physical work or to provide ratings of that physical work (Hassmén, 1991). Perceptions of exertion have also been experimentally manipulated by hypnotic suggestion (Albert & Williams, 1975; Morgan Hirta, Weitz, & Balke, 1976). Other researchers have concluded that physiological variables account for about two-thirds of variance in RPE with the remainder accounted for by psychological mediators such as extroversion-introversion and state-trait anxiety (Morgan; Noble et al., 1973). The associative cognitive strategies (attending to body signals) of elite marathon runners compared to dissociative strategies (potentially ignoring sensations of pain and discomfort) of less capable runners has also been hypothesised to contribute to perceived exertion (Morgan & Pollock, 1977).

Central Mediators of RPE

The central physiological processes thought to mediate signals of exertion are HR, V_E, oxygen consumption (VO_2), and carbon dioxide excretion (VCO_2; Noble & Robertson, 1996). Identifying the primary central signals involved in perceived exertion is difficult, however, because much of the research in this area is correlational. Attempts to manipulate central physiological processes experimentally and measure the effects on RPE have resulted in conflicting results (Pandolf, 1983; Watt & Grove, 1993).

Heart Rate (HR)

The HR response during exercise has been closely associated with RPE and, as mentioned earlier, formed an integral part in the development of the RPE scale (Borg, 1970). Researchers have suggested, however, that although HR correlates well with RPE, it is probably not a primary signal for the perception of exertion because it is unlikely that individuals consciously attend to HR during exercise (Robertson, 1982).

Correlational research. Correlational evidence dominates the HR-RPE literature. Borg's (1970) original work validating the 15-point RPE scale resulted in correlations between HR and RPE of around .80. As a rough approximation, Borg suggested that HR for middle-aged people working at medium intensity should be fairly close to 10 times the RPE value. Borg (1982) later emphasised that this proposed relationship was not intended to be taken too literally. He stressed that factors such as anxiety, age, environmental conditions, and mode of exercise all affect the relationship between HR and feelings of strain. Most research results have suggested that RPE covaries with HR during exercise. The strength of the relationship, however, may change under certain circumstances (e.g., when exercise involves different limbs) and at different exercise intensities.

The relationship between HR and RPE appears to hold for both continuous and intermittent exercise. Edwards et al. (1972) examined the relationship between RPE, HR, respiratory variables, and La during continuous and intermittent exercise at the same average power output. Participants ($N = 3$) performed paired tests of intermittent and continuous graded exercise on a cycle ergometer. The durations of the continuous exercise bouts were between six and 24 minutes depending on the workload presented. The intermittent exercise bouts lasted between 10 and 120 seconds and were alternated with 30 seconds of loadless pedaling. The total time of work at each workload and the overall exercise duration for the two tests was equal. RPE was recorded during the 30-second recovery period following each workload and physiological variables were recorded at baseline, after one-third and two-thirds of the total test time, and at completion of the tests. Strong correlations were found between HR and RPE during continuous and intermittent exercise (*r* = .88 and .86 respectively). When HR was measured as percentage of maximum, correlations remained strong (*r* = .89 and .87). Although the relationship between HR and RPE in this study appeared remarkably stable across different exercise protocols, the generalisablity of these results is questionable given the extremely small sample size. Another concern is the calculation of 10 pairs of correlation coefficients without reporting any adjustment of alpha levels. This practice increases the likelihood of making Type I errors.

Eston and Williams (1986) investigated the relationship between RPE, HR, and power output with 30 healthy adolescent boys (age range 15-17 years). RPE and HR were recorded at power outputs equivalent to 30, 60, and 90% of participants' VO_2max. Participants cycled for three to four minutes at each workload until HR had reached steady-state, at which time they were asked to rate their perceived exertion. A strong correlation was found between RPE and HR (*r* = .74). Equivalent associations were found between HR and power (*r* = .74) and RPE and power (*r* = .78). RPE ratings at 60% (*M* = 12.2, *SD* = 2.3) and 90% of VO_2max (*M* = 16.0, *SD* = 2.1) were similar to those reported in other studies with adult samples (Burke & Collins, 1984; Eston & Burke, 1984). The authors concluded that there was a close relationship between HR and RPE and that adolescents perceive exertion similarly to adults.

Although authors have reported strong correlations between HR and RPE, certain situations have been shown to disturb the relationship between HR and RPE. Gamberale (1972) assessed the relationship between RPE and multiple physiological variables with 12 male university students across a variety of physical tasks. He found that different physical activities could alter the relationship between RPE and HR. Participants performed graded exercise on a cycle ergometer using three, six-minute workloads (300, 600, and 900 kpm.min^{-1}) and a five-minute exhaustive bout. Participants also performed weight lifting exercises (three six-minute bouts, lifting weights [1.35, 3.35, and 5.35 kg] from shoulder height to a shelf 25 cm higher) and undertook pushing weights (6.0, 11.0, and 16.0 kg) in a wheelbarrow on a 100 metre course. Correlations between HR and RPE were strongest during graded exercise (r = .94) and weakened during lifting weights (r = .64) and during wheelbarrow work (r = .42). Supporting the idea that peripheral signals play a more important role in mediating perceptions of exertion, Gamberale reported that activities that elicited high La levels in relation to oxygen uptake (i.e., lifting weights), also elicited greater RPEs in relation to HR. Low La levels in relation to oxygen uptake during wheelbarrow work provided the lowest RPEs in relation to HR. The differences in strength of correlations between RPE and HR across different activities are also likely to be a result of the greater range of power levels presented in the bicycle work. Because the different activities resulted in different RPEs for a given HR, these results suggest that HR is unlikely to be a primary cue for perceptions of exertion.

Similar to the results presented above for different physical tasks, other researchers have demonstrated variations in the HR-RPE relationship during exercise using different limbs. Described in more detail in a later section on upper and lower body exercise, Sargeant and Davies (1973) examined changes in RPE relationships across one-arm, two-arm, one-leg, and two-leg exercise tests. Incremental exercise consisting of five 6-minute bouts were administered to six participants for each mode of exercise. Workloads were adjusted to account for lower exercise capacities for arm exercise. Correlations between HR and RPE were strong for leg exercises (one and two leg, respectively, r = .84 and .87) and moderate to strong for arm exercises (one and two arm, respectively, r = .79 and .65).

Corresponding with greater muscle mass and higher absolute workloads, leg-work resulted in higher HRs. Although RPEs were also higher during leg exercise, at a given HR, RPEs were higher for leg compared to arm exercises. When power outputs were adjusted to account for maximal exercise capacities, however, physiological and perceptual responses were similar between arm and leg exercise. The authors suggested that RPE was more closely associated with exercise intensities relative to maximal exercise capacity than to absolute workloads and HR.

Eston and Brodie (1986) reported similar results with 19 healthy participants using arm and leg-work on a modified cycle ergometer. The same absolute workloads were used for arm and leg exercises, and predictably, arm exercises produced higher HRs and RPEs compared to leg exercises. Similar to Sargeant and Davies (1973), for a given RPE, HR was higher for leg exercises than arm exercises. The magnitude of increase in HRs for arm compared to leg exercise (8% to 28%) at the same absolute workload was considerably less than the magnitude of increase in RPE (38% to 44%). These results point to the added contribution of local factors (e.g., La) in mediating RPE when smaller muscle masses are involved. Other researchers have reported greater La concentrations during arm compared to leg exercises at absolute workloads (Sawka, Miles, Petrofsky, Wilde, & Glaser, 1982). Although La was not measured in this study, greater V_E during arm compared to leg exercise (21% to 40%) may have resulted from isocapnic buffering of hydrogen ions (H^+) indicative of high La concentrations. These results, again suggest that HR is unlikely to be a primary mediator of RPE. In contrast with Sargeant and Davies, Sawka et al. reported stronger correlations between HR and RPE for arm exercises (r = .78) than for leg exercises (r = .62). This result may be because a greater range of HRs and RPEs were obtained in this study for arm compared to leg work.

Factors, such as pedal rate and illness, have also been shown to disturb the HR-RPE relationship. Löllgen, Ulmer, and von Neiding (1977) investigated the relationship between RPE and pedaling rate for healthy participants (*N* = 4) and patients with chronic obstructive lung disease (COLD; *N* = 4). Participants performed 16 one-minute exercise bouts with 90 seconds of rest between each bout. Four different workloads were employed (healthy; 5.0, 10.0, 15.0, and 20.0 $mkp.s^{-1}$; COLD; 2.5, 5.0, 7.5, and 10.0 $mkp.s^{-1}$) and four different pedal rates (40, 60, 80, and 100 rpm) applied to each workload. Pedal rate and workload were introduced in random order and HR and RPE recorded immediately upon completion of each workload. Overall correlations between HR and RPE were strong for healthy participants (r = .68 to .85), but lower for COLD patients (r = .49 to .74). Lower correlations for COLD participants may be the result of a smaller range of exercise intensities administered for this group. This difference in exercise intensity draws into question the validity of making direct comparisons of RPE relationships between the groups. For healthy participants, pedal rate affected the HR-RPE relationship in that higher pedal rates elicited lower RPEs but higher HRs. Although results were less consistent, the same trend was evident with COLD patients. These results suggest that, despite a strong association between HR and RPE, other factors, such as illness and pedal rate, can alter this relationship. Some research design issues, however, cast doubt over the reliability of these results. The small sample size limits the generalisability of these results, and exercise bouts over such a short duration are unlikely to elicit meaningful information about the relationship between RPE and HR responses. As discussed previously, any sensations of exertion perceived in the first 30 seconds of exercise are most likely entirely peripheral and rely on sensations associated with muscular contraction (Cafarelli, 1977). Further, central signals only become important mediators of exertion at higher exercise intensities (Robertson, 1982), which are unlikely to be achieved in one minute. HRs are also unlikely to have represented steady-state responses over such a short duration, thus underestimating HR responses at given workloads.

Different relative intensities during steady-state exercise have also been shown to alter the HR-RPE relationship. Garcin, Vautier, Vandewalle, Wolff, and Monod (1998) examined the relationship between RPE and HR during constant load exercise. At one-week intervals, participants ($N = 10$) performed three steady-state exercise tests to exhaustion on a cycle ergometer at 60, 73, and 86% of VO_2max. HR was recorded every minute, and overall and muscular RPE were collected every five minutes for the first 20 minutes of exercise and every 10 minutes thereafter. The authors reported a significant upward shift in HR-RPE regressions as relative exercise intensities increased. Calculations of effect sizes (Cohen's *f*; a calculation of the magnitude of difference between means) showed that variations in HR-RPE relationships across different steady-state workloads represented extremely large differences (RPE muscular, $f = 2.15$; RPE overall, $f = 2.15$). For a given RPE, HR depended on relative aerobic demand, with increases in HR for a given RPE between tests performed at 86 and 60% of VO_2max averaging 9% or 17 bpm. The authors concluded that, for constant load exercise, HR can increase without any change in RPE, and that HR is more closely associated with relative workload than with RPE.

Some researchers have reported very weak associations between HR and RPE. Jackson, Dishman, Croix, Patton, and Weinberg (1981) examined performance times, HR, and RPE responses for 67 college-age males during a self-paced 1.5 mile run in which participants were instructed to finish in the fastest time possible. Split times, HRs, and RPEs were recorded at 28 measurement points during the run and intercorrelations calculated. Correlations between HR and RPE varied greatly between -.31 and .60, with a mean correlation of .16. Despite HRs indicating steady-state performance during the middle laps of the run, RPE appeared to increase as a function of cumulative time and distance. The authors reported that the results indicated a negligible amount of common variance between RPE and HR, and did not support a central control model for RPE. The self-paced protocol, however, resulted in considerable variation between fastest and slowest lap times (21%). Negative correlations between HR and RPE predominated during the first half of the run. This was most likely due to fast times during the first three laps, when mean HRs increased rapidly to 182 bpm before levelling off, whereas RPE increased steadily throughout the trial. Such variability in running pace and intercorrelations between variables draws into question the validity of averaging 28 different correlations to conclude that HR is not closely related with RPE. The lack of association between HR and RPE at different stages of the run, however, suggests that HR is not a primary determinant of RPE.

Similarly, Koltyn, O'Connor, and Morgan (1991) reported low correlations between HR and RPE for male ($N = 31$) and female ($N = 31$) competitive swimmers. Participants completed a 200-yard swim in their specialty stroke at 90% of the swimmers best time. HR was recorded every 15 seconds throughout the swim and RPE was assessed immediately after each swim. A very weak correlation was found between RPE and HR for both men ($r = .04$) and women ($r = .06$). These remarkably low correlations (given the theoretical connection between RPE and HR), however, can be attributed to HR being calculated as an average of the whole swim, whereas RPE was recorded only after the swim was completed. The results from this research are fatally flawed by this study design.

Experimental research. Although the above studies have generally demonstrated a strong relationship between HR and RPE, authors are quick to point out that these results do not suggest a causal relationship between the variables (e.g., Pandolf et al., 1972). Alterations in the HR-RPE relationship between different exercise protocols and conditions suggest that HR is not a primary mediator of RPE. Researchers who experimentally manipulated HR and assessed RPE responses have also not supported HR as a primary cue for RPE.

The administration of drugs to alter HR responses during exercise has been used to examine HR-RPE relationships. Davies and Sargeant (1979) used intravenous injections of atropine and practolol to alter HR experimentally and assess accompanying RPE responses. Participants' ($N = 4$) HR, VO_2, and RPE were recorded during graded exercise to exhaustion and during one hour of prolonged exercise (graded walking at 60% of VO_2max) on a treadmill. The graded exercise involved increases in grade of three percent every eight minutes to exhaustion. Within-group comparisons were made between atropine, practolol, and control trials for each exercise protocol. During progressive exercise, practolol resulted in lower HRs at a given RPE, whereas, atropine resulted in higher HRs at a given RPE when compared to the control condition. At 2 $l.min^{-1}$ oxygen consumption, HRs were 30 bpm lower for the practolol trial and 10 bpm higher for the atropine trial when compared to the control condition. Oxygen consumption was not altered between the trials and exhibited strong correlations with RPE ($r = .92$). After 10 minutes of steady-state exercise RPEs were reported as similar in all trials, however, HR was 16 bpm lower in the practolol trial and 18 bpm higher in the atropine trial compared to controls. Examination of effect sizes showed very little change in RPE in the atropine trial ($d = .08$), and a small to medium increase in RPE in the practolol trial ($d = .32$). The authors concluded that HR is unlikely to be an important cue for the perception of exertion and that RPE appears more related to relative workload than to HR. This result supports the contention of others that, although RPE will covary with HR, HR is unlikely to be consciously monitored and, therefore, does not provide a primary sensory cue for RPE (Mihevic, 1981; Noble & Robertson, 1996).

Ekbom and Goldbarg (1971) employed a similar research methodology, using propranolol and atropine to manipulate HR experimentally. Participants (*N* = 14) performed three 6-minute submaximal workloads (25%, 50%, and 75% of VO_2max) and a separate maximal exercise test in control and experimental conditions. At maximal workloads, RPEs were the same in all trials, although HR was 38 bpm lower during the propranolol trial compared to the control and the atropine trials. At a submaximal HR of 125 bpm, mean RPE responses ranged from 8 (following atropine injections) to 15 (following propranolol injections), whereas the mean RPE for the control trial was 11. RPE was not significantly different between the three tests at a given VO_2, or when oxygen deficit, V_E, and La were controlled. Although insufficient data is presented to calculate differences between dependent variables, the magnitude of change in RPE between trials strongly supports the contention that HR is not a primary cue for perceptions of exertion.

Sjöberg, Frankenhaeuser, and Bjurstedt (1979) also used propranolol to lower HR experimentally during incremental cycle ergometer tests. Participants (*N* = 15) performed two tests, one following a propranolol injection and one following the injection of a placebo. Five incremental workloads (150, 300, 450, 600, and 750 $kpm.min^{-1}$) of 11 minutes duration were administered. Participants rested between each exercise load until HRs had returned to pre-exercise levels. RPE responses were recorded during the fifth minute of each workload and HRs recorded continuously throughout exercise. Three reaction-time tasks were presented during the last five minutes of each workload. An analysis of RPE and HR responses during the fifth minute of exercise revealed significant decreases (16-19%) in HR between the placebo and the propranolol trials, but no significant differences in RPE. The authors concluded that HR is not a prominent cue for perceived exertion. The small sample size in this study, however, raises the possibility of a

Type II error when interpreting no changes in RPE, because the non-significant difference translated into a large effect (*f* = .45). The low intensity at which exercise was performed in this study might also have affected the reliability of these results. Maximum mean HRs for the placebo group did not exceed 130 bpm. At such low exercise intensities, important mediators of RPE (e.g., La, V_E) were unlikely to have reached thresholds at which they make meaningful contributions to the perception of effort. Questions also remain regarding repeated bouts of exercise. Although the authors reported that participants rested between bouts until their HRs returned to pre-test levels, other mediators of exertion were not measured, the residual effects of which may have elevated RPE responses. The residual effects of these mediators may explain the unexpected result of large increases in RPE during the propranolol trial. The authors did not report in which order the experimental conditions were presented, or whether they were performed on the same day.

Heat stress has also been used to manipulate HR experimentally. Glass et al. (1994) compared measures of cardiovascular and perceptual strain for six participants during steady-state exercise in a variety of environmental temperatures (14.7°C, 21.0°C, and 27.4°C). As expected, HR was significantly elevated across time in the high temperature condition compared to the moderate and low temperature conditions. RPE, however, did not change between conditions and was consistent with VO_2 response. The authors concluded that RPE was closely related to metabolic work reflected in oxygen demand, but not to cardiovascular strain in moderate and high temperature conditions. Kamon, Pandolf, and Cafarelli (1974) compared physiological and perceptual responses during steady-state exercise at 40% of VO_2max for fit young men ($N = 10$) in moderate (24°C), hot (44°C), and extreme (54°C) temperature conditions. There were no significant differences in RPE between conditions, however, significant increases in HR were detected as environmental temperatures increased. It is questionable, however, whether the exercise demands were sufficient for important mediators of perceived exertion to influence RPE responses. Pandolf et al. (1972) also reported no significant differences in RPE between exercise performed at the same relative workload in different temperatures, despite significant increases in HR at higher temperatures. Maw, Boutcher, and Taylor (1993) reported similar results comparing exercise responses between moderate and hot conditions. Together these results suggest that increases in environmental temperatures provide additional cardiac stimulus that is not perceived by participants, and provides further evidence that HR is not consciously monitored and does not directly mediate RPE. These studies are reported in more detail in a later section on the effects of temperature on RPE.

Lewis et al. (1980) examined the effects of training specific limbs (arm training and leg training) on HR, RPE, and ventilatory responses during exercise tests involving trained and untrained limbs. Five sedentary young men participated in 11 weeks of arm training and five others participated in leg training. HR at a given submaximal workload was lower during trained and untrained limb testing following both arm and leg training. RPE responses, however, were lower only during trained limb exercises. These results suggest that changes in RPE responses following training are, in part, attributable to changes in local muscular physiology rather than central adaptations.

Albert and Williams (1975) examined the effects of post-hypnotic suggestion on the endurance capacity of nine young males during GXTs to exhaustion. HR, RPE, and endurance times for neutral, performance fatigue, and performance facilitation hypnotic conditions were compared with a baseline condition and a control group. Baseline responses were used to match participants who were randomly assigned to the hypnosis or control groups. The experimental groups received hypnotic suggestions (performance fatigue, performance facilitation) one hour prior to each test, whereas the control group met with the hypnotist but were not hypnotised. Mean HRs remained relatively stable across all experimental conditions (2-4% change from baseline). In the facilitative condition, however, RPE decreased (12%), and in the fatigue condition RPE increased (9%). RPE was reported to follow the administered suggestions rather than actual workload or cardiac output. These within group comparisons suggest that HR was not a primary cue for RPE. Between group comparisons, however, reveal inconsistent results. During the fatigue condition, the experimental group had a slightly lower mean HR ($d = .10$), but moderately elevated RPE responses ($d = .45$). During the facilitative condition, however, comparably lower RPE and HR responses ($d = .49$ and $d = .39$, respectively) were reported for the experimental group when compared to controls.

Allen and Pandolf (1977) demonstrated that varying the oxygen concentration in breathed air could alter the relationship between HR and RPE. Male participants ($N = 12$) exercised at 50% and 80% of VO_2max for 10 minutes while breathing normal and hyperoxic (80% O_2-20% N_2) air. HR, respiratory parameters, and RPE were measured during the first minute, the fifth minute, and tenth minute of exercise, and at regular intervals up to 20 minutes post-exercise. La was also measured during the first minute post-exercise. The authors reported no significant changes in HR or respiratory variables between the normal and hyperoxic conditions during exercise or during recovery, although HR and respiratory parameters were consistently lower in the hyperoxic condition during these periods. RPE was significantly reduced from the fifth minute of exercise to the fifth minute of post-exercise recovery in the hyperoxic compared to the normal condition. The authors reported that HR and the respiratory variables measured were not dominant factors in determining RPE and parallel reductions in RPE and La post-exercise suggest that La is more likely to be a primary cue for RPE. Not finding significant reductions in HR and respiratory variables during exercise in hyperoxic conditions, however, goes against experimental and theoretical expectations (Byrnes & Mullin, 1981; Mateika & Duffin, 1994) and raises questions regarding the reliability of these results.

Results from sleep deprivation research have also demonstrated alterations in the HR-RPE relationship. Martin (1981) examined the effect of sleep deprivation on exercise performance for eight physically active young adults. Participants performed graded treadmill exercise at 80% of VO_2max following normal sleep and again following 36 hours of sleep deprivation. Respiratory parameters, HR, and RPE were measured after 10 minutes of exercise and every seven minutes thereafter. Time to exhaustion was reduced by an average of 11% after sleep deprivation, but HR was not significantly or meaningfully altered by lack of sleep. Perceived exertion, however, was significantly greater following sleep deprivation over the exercise period. Minute V_E was the only physiological variable to show significant increases following sleep deprivation.

In summary, there is little doubt that HR and RPE responses during exercise are related. Researchers have suggested, however, that individuals are unlikely to attend to HR when making perceptual judgements of their exertion. This contention is supported by research findings that show alterations in the HR-RPE relationship in different experimental conditions. Further support is provided by researchers who have experimentally manipulated HR during exercise without reporting changes in RPE. The association between HR and RPE is a likely result of covariance with other mediators of perceptions of exertion, such as power output, workload, V_E and parameters associated with local muscular fatigue like La and pH.

Pulmonary Ventilation, Respiratory Rate, and Tidal Volume

Ventilatory sensations might be the only central signals of exertion that are consciously monitored by individuals (Pandolf, 1983; Robertson, 1982), especially at higher respiratory rates, when exercise demands stimulate the production of energy via the aerobic metabolism requiring the buffering of metabolic acidosis (Robertson & Metz, 1986). Both correlational and experimental evidence support the role of V_E in mediating central signals of exertion, but this mediating role may only be apparent at high metabolic rates when cardiorespiratory demand is great (Noble & Robertson, 1996). V_E is a function of RR and tidal volume (volume of air inspired or expired in each breath), and all three parameters are often measured together when assessing respiratory responses to exercise.

Correlational research. Correlational evidence suggests a functional relationship between ventilatory responses to exercise and perceptions of effort. In research briefly described in the previous section, Sargeant and Davies (1973) reported strong correlations between V_E and RPE for one and two limbed exercises ($r = .80$ to $.90$, respectively). These relationships were, however, influenced by the size of the muscle mass involved in exercise, with the larger muscle mass (leg exercises) eliciting greater V_E for a given RPE. Edwards et al. (1972) found strong correlations between RPE and V_E during intermittent ($r = .90$) and continuous exercise ($r = .94$). Edwards et al. also reported a moderate association between RR and RPE for continuous exercise ($r = .67$). Assessing the effect of temperature on RPE relationships, Kamon et al. (1974) reported a strong overall correlation between RPE and V_E ($r = .77$), whereas the association between RPE and RR was weaker ($r = .47$). These correlations were calculated during the last 15 minutes of exercise across all conditions. Pandolf et al. (1972) also examined RPE relationships in different environmental temperatures. Across all conditions during the first half of exercise (15 minutes) V_E correlated most highly with RPE ($r = .78$), whereas, during the last 15 minutes of exercise, RR correlated best with RPE ($r = .60$).

Noble et al. (1973) assessed cardiorespiratory and RPE responses from six participants during 30-minute, steady-state exercise bouts in moderate (24°C), hot (44°C), and extreme (54°C) temperature conditions. Three workloads were administered in 24°C, at 48%, 60%, and 68% of participants' VO_2max. The trials conducted in hotter conditions involved workloads equivalent to 48% of participants' VO_2max (determined in moderate conditions). Separate stepwise regression analyses were calculated using RPE as the dependent variable at minute-five, minute-15, and minute-30 for combined results from the moderate and hot conditions. V_E or RR were entered first in all six regression analyses. V_E was the major contributor to variance in RPE in moderate and hotter conditions at minute-five (moderate $R^2 = .31$; hot $R^2 = .32$) and at minute-15 (moderate $R^2 = .56$; hot $R^2 = .46$). By minute-30, however, RR was the primary contributor to variance in RPE in both conditions (moderate $R^2 = .41$; hot $R^2 = .23$). These results support those from Pandolf et al. (1972), that RR may be a more important cue for RPE than V_E at high physiological workloads. It is difficult, however, to separate the relative contribution of V_E and RR to RPE because of the likely high degree of multicolinearity between these two variables in particular (V_E is a product of RR and tidal volume), and the other variables entered into the regression. Also of concern is the small sample size, whereby the number of independent variables (eight) in the regression analyses exceeded the number of participants. Although the objective of this research was stated as "exploratory", stepwise regression analyses with such a small sample size means these results should be viewed with caution. Stepwise regression analyses require a 40 to 1 participant to variable ratio (Tabachnick & Fidell, 1996). The researchers have risked overfitting the data, severely limiting generalisability. Also, a thorough examination of the variables accounting for the most variance in perceived exertion should include peripheral mediators of RPE, such as La.

Vanden Eynde and Ostyn (1986) reported significant correlations between RPE and V_E, and RPE and RR during bicycle ($r = .58$ and $.57$, respectively) and treadmill exercise ($r = .50$ and $.38$, respectively). The lower correlations reported might be due to the relatively small work intensity range from which coefficients were calculated (68% to 100% of VO_2max). Toner, Drolet, and Pandolf (1986) found a moderate correlation ($r = .61$) between RPE and V_E across three types of exercise (arm, leg, and combination) performed in two water temperature conditions (26°C and 20°C). These correlational studies suggest a functional relationship between RPE and V_E over a range of exercise intensities and exercise conditions. Research where V_E is experimentally manipulated, however, provides the strongest evidence for V_E as a physiological mediator of RPE.

Experimental research. One way to alter V_E experimentally and measure the effect on RPE is to change the oxygen (O_2) content of inspired air. During submaximal exercise, hyperoxic conditions decrease V_E, whereas, hypoxic conditions increase V_E. Pedersen and Welch (1977) investigated the physiological and perceptual responses of six healthy young males performing progressive exercise to exhaustion while breathing normal (21% O_2) and hyperoxic air (50% and 80% O_2). As oxygen concentration increased, V_E decreased at all workloads. In concert with changes in V_E, RPE responses were significantly lower when participants were breathing 50% compared to 21% O_2. In the 80% O_2 condition, however, changes in RPE were only evident at the highest workload. The authors proposed that it might be possible to add O_2 in excess, resulting in an increase in RPE for which they had no theoretical explanation. Pedersen and Welch also reported that variations in La concentrations were consistent with changes in V_E, and concluded that V_E and La were likely contributors to reductions in perceived effort in the 50% O_2 condition. These results highlight the methodological difficulties of using different oxygen concentrations to investigate causal relationships between ventilatory variables and RPE. The functional relationship between La metabolism and V_E (i.e., respiratory compensation of metabolic acidosis) means that alterations in O_2 concentration will have concomitant effects on both respiratory function and variables associated with local muscular sensations (e.g., La, pH).

It is, therefore, difficult to ascertain whether alterations in RPE in hypoxic and hyperoxic conditions are due to changes in V_E or local muscular parameters.

High altitude exercise testing is another method researchers have used to examine the relationship between ventilatory variables and RPE. Low air pressure at high altitude leads to hypoxia and increases in V_E. Details of these studies are reported in a later section that examines RPE responses at altitude. Exercise responses at altitude support V_E as a primary mediator of RPE. Young et al. (1982) reported responses from eight low-altitude residents performing 30 minutes of steady-state exercise (85% of VO_2max) at sea level and after acute exposure to altitude (4,300 m). Although submaximal VO_2 was significantly reduced with large increases in respiratory effort, RPE and V_E were not significantly altered. Sufficient information was not provided to compare the magnitude of change for RPE and V_E responses. Why V_E did not significantly increase during acute high altitude exercise (as would be theoretically expected) was not explained. Maresh, Kraemer, Noble, and Robertson (1988) tested short-term (10 to 21 days; n = 52) and long-term residents (greater than two years; n = 55) at altitude during GXTs to voluntary exhaustion at 2,200 metres. At 60% of VO_2max, short-term residents had significantly elevated V_E and RPE compared to long-term residents, whereas other respiratory-metabolic parameters demonstrated little change. Although perceptual and respiratory responses differed between these two studies, similar RPE and V_E responses support the contention that V_E is consciously monitored during exercise, but other respiratory variables are not (Robertson, 1982).

Robertson et al. (1986) examined the effect of induced alkalosis on RPE, blood pH, and central signals of perceived exertion. An alkalotic shift in blood pH should reduce the demand for isocapnic buffering of H^+s and respiratory compensation for metabolic acidosis (Kowalchuk, Heigenhauser, & Jones, 1984), thus decreasing V_E and possibly attenuating RPE. Participants ($N = 10$) performed arm, leg, and a combination of arm and leg exercises after bicarbonate ingestion (administered to induce alkalosis) and again in a placebo trial. Participants performed GXTs to exhaustion for each mode of exercise with RPEs (arm, leg, central, and overall), HR, V_E, RR, and tidal volume recorded during each minute of exercise. Blood pH was measured prior to substance ingestion, immediately prior to exercise, and at 80% of VO_2max. Alkalosis did not affect perceptual or physiological parameters at 20%, 40%, or 60% of VO_2max. At 80% of VO_2max significant reductions in V_E, RR, and all measures of RPE were observed, but VO_2, HR, and tidal volume were not affected by alkalosis. The authors concluded that V_E and RR (but not tidal volume) were primary mediators of central perceptions of exertion and discomfort, but only at higher exercise intensities, where metabolic acidosis becomes a factor in limiting exercise capacity. Although insufficient information was presented with which to calculate effect sizes, mean differences and graphical representations of dependent variables clearly support the authors' conclusions.

Another method used to manipulate V_E experimentally is increasing the percentage of CO_2 in inspired air. Inspiration of CO_2 results in increases in V_E, but no increase in HR or oxygen intake at a given energy expenditure (Menn, Sinclair, & Welch, 1970). Cafarelli and Noble (1976) investigated the effects of hypercapnia on healthy young men ($N = 10$) during treadmill running and cycling. Three, 5-minute workloads were presented in random order for cycling (300, 600, and 900 $kpm.min^{-1}$) and running (4.8, 8, and 11.2 $km.h^{-1}$), with five minutes rest between trials. Each exercise session was completed under normocapnic and two hypercapnic (+ 1.75% CO_2 and + 3.50% CO_2) conditions. HR, RR, V_E, tidal volume, and RPE were recorded throughout the exercise trials. The authors reported that the percentage of inspired CO_2 proportionally increased V_E and tidal volume at all exercise intensities during cycling and running, but did not affect HR or oxygen uptake. RR only changed in relation to exercise intensity and remained unaltered between experimental conditions. Greater concentrations of CO_2 also increased RPE responses, although these were only significantly different from the normal condition at the highest concentration of CO_2 during the highest running workload. This result was not unexpected because the highest running workload represented, on average, 71% of participants' VO_2max. Lower exercise intensities are unlikely to induce sufficient increases in V_E to act as a primary signal of exertion. There were no significant differences in RPE during cycling, but the highest exercise intensity attained during these trials was only approximately 55% of VO_2max. These results are consistent with previous research and suggest that V_E only becomes a primary signal of RPE at higher metabolic intensities.

In research described earlier, Martin (1981) found that V_E during exercise was the only physiological variable that increased following sleep deprivation in concert with increases in RPE. Although RPE was significantly higher following sleep deprivation at all time points during steady-state exercise (80% of VO_2max), V_E was only significantly greater at the last two time points (minute-24 and 31). Other researchers have used hypnosis (Morgan et al., 1976), variations in pedal frequency (Robertson, Gillespie, McCarthy, & Rose, 1979), testing mode (Franklin, Vander, Wrisley, & Rubenfire, 1983), and red blood cell infusion (Robertson, 1982) to support V_E as a principal signal for RPE.

Not all evidence supports V_E as a perceptual signal of exertion. In research described earlier, Allen and Pandolf (1977) reported that breathing hyperoxic mixtures attenuated RPE, but not V_E. The results of this research are bought into question, however, because the hyperoxic condition did not result in theoretically expected reductions in V_E. Also, Löllgen, Graham, and Sjogaard (1980) measured RPE and physiological responses to varying pedal frequencies. Changes in RPE were independent of changes in V_E at zero-load, and loads equivalent to 70% and 100% of VO_2max.

The association between V_E and RPE appears more related to RR as a perceptual signal of exertion than tidal volume. A common sense understanding of the sensory perception of respiration would suggest that the frequency of breathing is more likely to be consciously perceived than the volume of air inspired. Experimental evidence supports this contention. Robertson et al. (1986) demonstrated that changes in RPE followed changes in RR and V_E, but not changes in tidal volume. Robertson et al. (1979) examined the effects of varying pedal rates (40, 60, and 80 rpm) at a constant power output on RPE and physiological responses. Higher differentiated RPE responses were accompanied by higher RR and V_E responses at the slowest pedal rate. Also, Robertson and Metz (1986) reported that induced alkalosis decreased V_E and RPE at 80% of VO_2max but had no affect on tidal volume. Robertson and Metz concluded that RR was one of the primary mediators of respiratory-metabolic signals of exertion.

Research results support a role for ventilatory variables as important cues for perceived exertion at higher metabolic demands (Cafarelli & Noble, 1976; Noble & Robertson, 1996; Pandolf, 1983). At a critical metabolic rate, around 70% of VO_2max, V_E becomes an important signal for perceptions of exertion as RR increases. This metabolic rate approximately coincides with the lactate threshold (LT), where the buffering of metabolic acidosis becomes inadequate and begins to limit exercise capacity. It is likely, therefore, that the sudden emergence V_E as an important perceptual cue for RPE may be linked to local factors associated with La production and removal.

Oxygen Consumption (VO_2)

VO_2 is the amount of oxygen inspired and used by the body to fulfil immediate metabolic demands. The relationship between RPE and VO_2 is mediated by the V_E required to support aerobic metabolism (Noble & Robertson, 1996). It is unlikely, however, that individuals consciously perceive the amount of oxygen their bodies are consuming. As reported in the previous section, individuals attend to V_E and RR which, in turn, mediate VO_2. Mihevic (1981) cautioned that no evidence exists supporting the conscious monitoring of VO_2, and that relative oxygen consumption, as a perceptual cue, may be mediated by other, more easily monitored physiological responses.

Given the close connection between VO_2 and V_E, it is not surprising that research results have shown good correlations between VO_2 and RPE. In research reported earlier, Edwards et al. (1972) reported strong correlations between VO_2 and RPE for intermittent ($r = .92$) and continuous exercise ($r = .97$). Toner et al. (1986) reported a moderate correlation between VO_2 and RPE ($r = .51$) with participants working in cold and cool water using different limbs. Vanden Eynde and Ostyn (1986) also found moderate correlations between VO_2 and RPE for treadmill (*Tau-b* = .46) and cycle ergometer exercise (*Tau-b* = .49). The weaker correlations reported in these studies might be attributable to low exercise intensities (Toner et al.), a relatively small exercise intensity range, and the questionable use of an ordinal measure of association (Vanden Eynde & Ostyn).

There appears to be a stronger association between RPE and relative oxygen consumption, measured as a percentage of VO_2max, than between RPE and absolute VO_2. Sargeant and Davies (1973) reported correlations ranging from .76 to .88 between absolute VO_2 and RPE for one and two limbed arm and leg exercises. Stronger correlations ranging between .88 and .96 were reported between RPE and VO_2 as a percentage of VO_2max. Robertson et al. (1982) reported lower RPE responses during exercise in normoxic conditions compared to hypoxic conditions at a given absolute VO_2. When a lower VO_2max in acute hypoxic conditions was accounted for, however, RPE responses remained constant compared to normoxic conditions.

Pandolf, Billings, Drolet, Pimental, and Sawka (1984) compared RPE and physiological responses of nine healthy young males during arm crank and cycle ergometer tests at absolute (1.6 $l.min^{-1}$) and relative (60% of VO_2max) levels of VO_2. Discontinuous arm crank and cycle ergometer tests were performed to determine comparable individual power outputs for steady-state arm crank and cycle work. With at least three days separating each of four exercise tests, participants performed steady-state arm crank and cycle ergometer work for 60 minutes at power outputs corresponding to a VO_2 of 1.6 $l.min^{-1}$ and 60% of ergometer specific VO_2max. Differentiated RPEs, cardiorespiratory variables, and blood pressure were recorded every ten minutes and La determined every 20 minutes of exercise. Arm crank and cycle ergometer tests were reported to elicit similar relative (59 and 62% of VO_2max respectively) and absolute (1.57 and 1.64 $l.min^{-1}$ respectively) O_2 consumption. Local, central, and overall RPEs were significantly lower for cycle compared to arm exercises at all time points at absolute workloads. RPEs during the relative workload tests were not significantly different during arm and leg exercises. The authors concluded that RPE was more closely related to exercise intensities regulated according to relative VO_2 than absolute VO_2. Graphical representations of results, however, suggest that RPEs were not "the same" at relative exercise intensities. No means, standard deviations, *F*, or *t* values were reported and, therefore, effect sizes could not be calculated. Results from regression analyses used to determine the important predictors of RPE during arm and leg exercise will be reported in a later section pertaining to perceived exertion during upper and lower body exercise.

Haskvitz et al. (1992) used training adaptations to assess the stability of RPE at absolute and relative exercise intensities. RPE and VO_2 responses at the LT, FBLCs (2.0, 2.5, and 4.0 $mmol.l^{-1}$) and maximal exercise were compared between sedentary controls

($n = 7$), a group that trained at velocities associated with LTs ($n = 9$), and a group that trained at velocities greater than LTs ($n = 9$). Significant increases in VO_2 were observed for the trained groups at LT and FBLCs that also represented a greater percentage of VO_2max. These increases in absolute and relative cardiorespiratory capacities, however, were not associated with significant changes in RPE. Despite the authors reporting RPEs as not significantly different, post-training RPEs were consistently greater when compared to pre-training responses. An examination of the percentage change in perceptual and relative VO_2 responses reveals that, at exercise intensities above 70% of participants' VO_2max, changes in RPE (LT group, 3.1 to 10.5%; >LT group 6.1 to 10.9%) and relative VO_2 (LT group, 4.0 to 10.5%; >LT group 9.4 to 17.1%) following training were comparable. These results support the contention that RPE is more closely associated with VO_2 relative to maximal output than absolute VO_2 responses.

In research described earlier, Davies and Sargeant (1979) used intravenous injections of atropine and practolol to investigate a possible casual connection between HR and RPE. The researchers reported that changes in RPE between experimental conditions were independent of changes in HR. Moreover, during short-term progressive exercise in all conditions, RPE varied in accordance with relative exercise intensity measured as a percentage of VO_2max ($r = .94$). During prolonged exercise (60 minutes) at workloads associated with 60% of participants' VO_2max, however, RPE progressively increased over time despite VO_2 remaining unchanged. These results suggest that, although RPE might be associated with the percentage of VO_2max during short-term incremental exercise, this relationship breaks down during long-term steady-state exercise. This result might be explained by greater contributions to RPE made by feelings of local muscular fatigue as duration of exercise increases.

Some researchers have not reported results that support a close association between RPE and percentage of VO_2max. Comparing participants' responses during exercise with different exercise modalities, Hetzler et al. (1991) reported that RPE remained constant at the LT and FBLCs despite wide variations in the percentage of VO_2max. Similar results were found when comparing the effects of training on RPE relationships. RPE was found to be constant at the LT, despite this threshold occurring at higher percentages of VO_2max in trained individuals (DeMello et al., 1987; Seip, Snead, Pierce, Stein & Weltman, 1991). Boutcher et al. (1989) compared the effect of 10 weeks of differentiated training (cycling and running) on RPE and VO_2 at LT. In contrast to Haskvitz et al. (1992), Boutcher et al. reported different RPE and VO_2 responses at the LT. Despite LTs occurring at markedly greater levels of absolute and relative VO_2, participants' RPEs were actually reduced at the LT. These results suggest that RPE, relative to both La concentration and VO_2, might be attenuated by training. The finding that training resulted in opposite effects on VO_2 and RPE suggests that oxygen consumption is unlikely to be a primary mediator of RPE. These results have, in part, lead to the suggestion that La accumulation may be a more potent cue for RPE than percentage of VO_2max (Noble & Robertson, 1996). This contention is supported by other research findings that suggest RPE is lower at a given percentage of VO_2max following training (Hill, Cureton, Grisham, & Collins, 1987; Skrinar, Ingram, & Pandolf, 1983; Travlos & Marisi, 1996).

Research evidence suggests that the percentage of VO_2max, but not absolute VO_2, might play a mediating role in the perception of effort. Confounding results reported by researchers who have assessed the relationship between RPE and VO_2 at various La concentrations might reflect the integration of multiple systems in exercise performance and the perception of effort. The onset of La accumulation is associated with many alterations in ventilatory parameters. Although RPE may be associated with changes in

VO_2, other related parameters such as V_E and La accumulation may offer more pertinent perceptual cues for exertion.

Carbon Dioxide Excretion (VCO_2)

Exercise induced metabolic demands lead to increases in carbon dioxide (CO_2) excretion. As exercise intensity increases beyond 60% of VO_2max, blood pH decreases, La concentrations increase, and increasing concentrations of H^+ are buffered by bicarbonate (HCO_3^-). This process induces greater V_E and increased production and expiration of CO_2. As with other ventilatory parameters, VCO_2 is more likely to act as a mediator of RPE at higher exercise intensities (Noble & Robertson, 1996). Similar to the consumption of oxygen, it is unlikely that VCO_2 is consciously monitored during exercise. Associations between RPE and VCO_2 are likely due to the conscious monitoring of V_E, which covaries with VCO_2 at higher metabolic intensities.

In research described in the previous section, Cafarelli and Noble (1976) investigated the effects of hypercapnia on young men ($N = 10$) during treadmill running and cycling. Exercise bouts completed under normocapnic and two hypercapnic (+ 1.75% CO_2 and + 3.50% CO_2) conditions indicated that the percentage of inspired CO_2 proportionally increased V_E at all exercise intensities and increases in RPE were consistent with changes in V_E. Increases in RPE between the normocapnic and two hypercapnic conditions were, however, only statistically significant at the highest running workload. The highest workload (71% of VO_2max) might represent a crucial threshold where isocapnic buffering of metabolic acidosis requires a proportional increase in V_E. Increased V_E is, in part, due to the need to excrete CO_2. Despite VCO_2 being unlikely to be consciously monitored, increases in V_E, partly as a result of greater CO_2 production and removal, appear likely to mediate respiratory-metabolic signals of exertion.

As described previously, Pandolf et al. (1984) reported RPE and physiological responses from nine healthy young males during arm crank and cycle ergometer tests. Results from multiple regression analyses showed that VCO_2 accounted for small amounts of variance in overall RPE during cycle and arm crank exercise bouts at absolute workloads (R^2 = .09 and .13, respectively). Other results from multiple regression analyses used to predict physiological contributors to RPE in hot and neutral conditions found that VCO_2 contributed negligible amounts of variance in RPE (Noble et al., 1973). As with Pandolf et al., however, other related variables were entered into the regression analyses prior to VCO_2. The multicolinearity of VCO_2 with other respiratory variables in these regression analyses may obfuscate the unique variance VCO_2 shares with RPE.

Researchers have inferred that VCO_2 may be a mediator of RPE through its close connection with other respiratory variables, such as V_E. A precursor to increased V_E at higher metabolic demands is isocapnic buffering of excess H^+ produced during energy production to meet physiological demands. Increased VCO_2 is an integral part of the process to remove excess H^+ and alleviate metabolic acidosis. VCO_2 and RPE responses are likely to covary with exercise demands, particularly at higher exercise workloads.

Peripheral Mediators of RPE

Peripheral mediators of RPE are usually localised around the working muscles, but do involve integrated physiological systems (e.g., the delivery of oxygen and energy substrates to working muscles). Metabolic acidosis (La and pH), percentage of fast and slow-twitch fibres, muscle blood flow, and blood-borne energy substrates are recognised as peripheral mediators of perceptions of effort (Noble & Robertson, 1996).

Blood Lactate (La)

La is considered to affect RPE at higher exercise intensities when rates of anaerobic glycolysis produce excess La. Research findings have shown that exercise intensities need to reach a certain threshold (e.g., LT) before La becomes an important mediator of RPE (DeMello et al., 1987; Robertson et al., 1986). It is difficult, however, to distinguish the effects of La on RPE from other factors that also limit exercise capacity at higher intensities and coincide with threshold increases in La (e.g., greater concentrations of H^+ and lower pH, greater V_E). This integration of metabolic variables potentially contributes to past research findings that suggested a strong association between La and RPE, but reported inconsistent results when La and RPE were compared across experimental conditions or when La concentrations were altered experimentally.

Correlational research. Reviews of RPE literature have cited substantial correlational evidence to suggest that La may mediate perceptions of exertion (Carton & Rhodes, 1985; Noble & Robertson, 1996). In addition, researchers have demonstrated similar negatively accelerating functions for La and RPE across exercise time (Gamberale 1972; Ljunggren, Ceci, & Karlsson, 1987).

Strong associations between RPE and La have been reported under a variety of conditions. Edwards et al. (1972) found the relationship between RPE and La was robust when looking at intermittent and continuous exercise. Significant correlations have also been reported between La and RPE across exercise modalities (Hetzler et al., 1991), environmental temperatures (Bergh, Danielsson, Wennberg, & Sjödin, 1986), gender (Purvis & Cureton, 1981), and normoxic and hyperoxic conditions (Allen & Pandolf, 1977). In support of the contention that La mediates RPE at higher, but not lower, exercise workloads, DeMello et al. (1987) reported strong correlations between La and RPE above the LT for trained and untrained men and women.

Reports that RPE correlates well with La at LT and FBLCs above the LT have led researchers to investigate the efficacy of moderating exercise intensities using RPE. This application of RPE is useful for exercise prescription because the LT falls within the training zone for cardiorespiratory conditioning and changes to the LT are considered indicative of peripheral training adaptations (Noble & Robertson, 1996). Stoudemire et al. (1996) used an incremental exercise test to determine the RPE, VO_2, treadmill velocity, and HR associated with FBLCs of 2.5 $mmol.l^{-1}$ and 4.0 $mmol.l^{-1}$. Participants ($N = 9$) were then asked to complete two 30-minute runs at an RPE corresponding to each FBLC. HRs, VO_2, and treadmill velocities were consistently below criterion levels throughout the 30-minute runs performed at 2.5 $mmol.l^{-1}$ and 4.0 $mmol.l^{-1}$. Despite the authors claiming that RPE can be used to produce La concentrations that are "reasonably close" to criterion values, the results suggested some variability in La responses while RPE remained constant. Although La concentrations were generally not significantly different from criterion values, they were also not the same. La concentrations varied from approximately 2.25 to 3.0 $mmol.l^{-1}$ for the 2.5 $mmol.l^{-1}$ run and from approximately 3.2 $mmol.l^{-1}$ to 4.5 $mmol.l^{-1}$ for the 4.0 $mmol.l^{-1}$ run. Despite the contention of the authors that RPE is a valid tool for prescribing exercise at certain FBLCs, the results suggest that La-RPE relationships may not be transferable from incremental tests to steady-state exercise.

Some correlational research does not support the close association between La and RPE, although methodological issues bring into question the reliability of some results. Löllgen et al. (1980) investigated the effect of varying pedal rate, while maintaining a constant power output (zero load, power at 70% VO_2max, and power at maximal) on associations between RPE and central and peripheral mediators of RPE. RPE and La increased with increases in power output, but when power output was controlled for, the correlation between La and RPE was not significant. Moreover, the authors found no significant correlations between RPE and any of the selected physiological variables, concluding that no single central or peripheral factor dominates the perception of exertion. The authors did not, however, report the actual magnitude of nonsignificant associations between RPE and physiological responses. In addition, La-RPE correlations were calculated by combining responses from tests performed at 70% of VO_2max and maximal effort. For correlation calculations, all pairs of observations of variables must be independent. By calculating correlations across two different conditions, the authors violated a basic assumption of correlations. Also, an examination of mean La and RPE responses at different workloads suggests that La and RPE responses followed similar patterns during the 70% of VO_2max test but not at maximal exertion. Tests performed at maximum effort consisted of work bouts of between 2.5 and 5 minutes. It is possible that La concentrations had not reached steady-state during these bouts resulting in an underestimation of the La response (Foxdall, Sjödin, & Sjödin, 1996). Given the small sample size and these methodological and analytical issues, it is not surprising that correlations calculated between La (or any other physiological variable) and RPE were not significant.

More recent research results question the stability of RPE responses at the LT and 4.0 $mmol.l^{-1}$ FBLC. Grant et al. (2002) examined the reproducibility of running velocity, HR, and RPE at the LT and 4.0 $mmol.l^{-1}$ FBLC with 36 physically active participants during two continuous incremental treadmill protocols performed at least one week apart. The overall between test correlations for the physiological and perceptual variables were strong, but varied according to the fitness of participants. Participants whose LT occurred at less than 10.5 $km.h^{-1}$ (unfit group) had strong correlations for RPE at the LT ($r = .78$) and 4.0 $mmol.l^{-1}$ ($r = .79$), but participants whose LT occurred at greater than 10.5 $km.h^{-1}$ (moderately fit group) had weaker correlations at the LT ($r = .43$) and 4.0 $mmol.l^{-1}$ ($r = .46$). The moderately fit group, however, was better at reproducing velocities and HRs between the two tests compared to the less fit group. These results suggest that RPE might not be effective for moderating training intensities corresponding to La accumulation. The decision to median split a continuous variable into groups according to fitness, however, casts doubt over whether fitness might affect the reproducibility of RPE responses. For a discussion about limitations of dichotomising a continuous variable in research see Cohen (1983).

Experimental evidence. Research designed to manipulate La experimentally and measure corresponding changes in RPE, or comparisons of La and RPE responses across experimental groups or conditions have shown inconsistent results (Noble & Robertson, 1996). Ekblom and Goldbarg (1972) reported that RPE was stable for given La concentrations during arm and leg exercises, during cycle and treadmill exercises, and before and after eight weeks of physical conditioning. Some studies have suggested, however, that the La-RPE relationship might be affected in particular conditions. Borg, Hassmén, and Lagerström (1987) reported that at a given RPE, La concentrations were greater during arm compared to leg exercise. Researchers have also reported that elevations in La in hot conditions compared to moderate temperature conditions did not transfer to greater RPE responses, particularly when workloads were high enough to induce sufficient heat induced increases in La (Bergh et al., 1986; Glass et al., 1994).

To determine the effect of exercise intensity on the La and RPE responses, Steed et al. (1994) assessed RPE during 30-minute steady-state protocols at velocities associated with the LT and FBLCs greater than the LT (2.5 & 4.0 $mmol.l^{-1}$). Exercising for 30 minutes at velocities associated with the LT, RPE responses of participants increased from nine to 11, whereas La concentrations remained stable. Exercising for 30-minutes at FBLCs greater than the LT, however, resulted in RPE and La values rising over time. These results suggest that workloads need to reach a particular intensity before La becomes an important mediator of RPE. Kolkhorst, Mittelstadt, and Dolgener (1996) reported similar results when they examined differences in RPE between uphill, downhill, and level treadmill running at velocities associated with 2.0 and 4.0 $mmol.l^{-1}$ FBLCs.

Treadmill velocity associated with both FBLCs increased significantly between uphill and level running, and between level and downhill running. In conjunction with differences in treadmill velocity (and HR), RPE significantly increased from uphill to level (9.5 to 10.5) and from level to downhill (10.5 to 12.5) running at 2.0 $mmol.l^{-1}$ FBLC (representing 69% of VO_2max). At 4.0 $mmol.l^{-1}$ FBLC (representing 83% of VO_2 max), however, there were only small nonsignificant differences in RPE between the different exercise gradients. These results suggest that, at lower exercise intensities, factors other than La mediate RPE responses. Running velocity might be an important cue for perceptions of effort at low exercise intensities or early during exercise bouts. This suggestion is supported by a strong correlation between treadmill velocity and RPE when running at velocities corresponding to 2.0 $mmol.l^{-1}$ FBLC ($r = .70$), and a weak correlation between these variables when running at velocities corresponding to 4.0 $mmol.l^{-1}$ FBLC ($r = .25$; Kolkhorst et al.). In further support of this conclusion, Cafarelli (1977) suggested that during the first 30 seconds of exercise the sensation of effort is entirely peripheral and depends on the force of muscle contraction.

The stability of perceptual responses at given La concentrations have been examined across participants of varying fitness levels. These studies are reported in more detail in a later section on training and RPE. Foster et al. (1999) reported HR and RPE responses associated with the LT and FBLCs (2.5 and 4.0 $mmol.l^{-1}$) for a group of world-class speed skaters during deconditioned and conditioned phases of their training. The authors reported that, although power outputs at FBLCs were significantly higher during the conditioned phase of the athletes' training, HR and RPE were not meaningfully different. Seip et al. (1991) compared the RPE and cardiorespiratory responses of runners ($n = 20$) and nonrunners ($n = 29$) at the LT and FBLCs (2.0, 2.5, and 4.0 $mmol.l^{-1}$). The authors reported no differences in local, peripheral, or overall RPE between the groups, despite runners attaining significantly higher treadmill velocities and greater V_E, VO_2, and HR at FBLCs compared to nonrunners. There was a tendency, however, for runners to exhibit higher central RPE responses at the two higher workloads. The lack of meaningful differences in local and overall RPE at FBLCs between runners and nonrunners, despite alterations in other mediators of RPE (i.e., V_E, running velocity) suggests that La is an important mediator for perceptions of exertion.

Haskvitz et al. (1992) questioned whether the relative intensity of training would affect RPE relationships differently. RPE and VO_2 responses at the LT, FBLCs (2.0, 2.5, and 4.0 $mmol.l^{-1}$), and maximal workload were compared between sedentary controls ($n = 7$), a LT trained group ($n = 9$), and a >LT trained group ($n = 9$). The LT group trained for one year at training velocities associated with their LTs. The >LT group trained for one year at a velocity half way between their LT velocities and their maximal running velocities. Significant increases in VO_2 and running velocity were observed for the trained groups at the LT, FBLCs, and maximal workload, with the >LT group improving more than the LT or control groups. Despite these changes in workload and cardiorespiratory demand, RPE was not significantly different at any test point. A close examination of RPE differences at given La concentrations suggest, however, that RPEs were greater at testing points following training due to a shift to the right in the La-power curve that came with training. These changes in RPE would reflect increases in reported running velocities at FBLCs following training. Rather than being closely linked to FBLCs, these results suggest that increases in respiratory demand and actual workloads may contribute to increased RPE responses.

The stability of RPE at the LT and FBLCs has also been demonstrated across exercise modalities. Hetzler et al. (1991) compared the RPE, HR, and VO_2 responses at the LT, FBLCs (2.0, 2.5, and 4.0 $mmol.l^{-1}$), and maximal exercise for 29 untrained male participants during cycle ergometer and treadmill exercises. Despite significant and meaningful increases in HR and VO_2 at the LT, FBLCs, and maximal exercise for treadmill compared to cycle exercise, no significant or meaningful differences were found for RPE. The authors concluded that RPE remains stable at the LT and FBLCs across exercise modalities for leg exercise. Other studies have also reported similar La-RPE relationships between different exercise modalities (Ekblom & Goldbarg, 1972; Gamberale, 1972).

Exercise tests performed under normoxic and hyperoxic conditions have been used to manipulate La experimentally and assess corresponding changes in RPE. Allen and Pandolf (1977) measured the cardiorespiratory and RPE responses of 12 males under normal (21% O_2) and hyperoxic (80% O_2) conditions. Significant reductions in post-exercise La concentration were matched by significant reductions in RPE. This result is in contrast, however, to Pedersen and Welch (1977), who compared the RPE, La, and cardiorespiratory responses of six healthy, young men breathing normoxic (21% O_2) and hyperoxic (50% and 80% O_2) gases. During a GXT, measures were taken at 75, 150, and 225 W. Reductions in La concentrations were reported as O_2 concentration increased. Changes in RPE, however, were not consistent. The authors reported significant reductions in RPE during the 50% O_2 condition compared to 21% O_2 at 75 W (10% reduction), 150 W (9% reduction), and 225 W (12% reduction). Smaller reductions in RPE were reported between the 80% and the 21% O_2 conditions at 75 W (no mean difference) and 150 W (2% reduction), with a significant difference only being reported at 225 W (8% reduction). This result suggests that increased O_2 concentration attenuates physiological demand. Accompanying reductions in RPE, however, appeared dependent on the relative amount of O_2 present, with excessive O_2 concentrations having little effect on perceptual responses. These studies appear consistent with other literature that reports lower La concentrations under hyperoxic conditions (Adams & Welch, 1980; Plet, Pedersen, Jense, & Hanse, 1992). More research is needed, however, to determine the effect of hyperoxic conditions on the RPE-La relationship.

Altitude exposure is another condition under which La concentrations may be altered. Depressed La concentrations at relative exercise intensities have been reported during acute altitude exposure (Maher, Jones, & Hartley, 1974). Young et al. (1982) tested the influence of acute (<2 hours) and chronic (18 days) high altitude (4,300 m) exposure on the RPE and physiological responses of eight low-altitude residents. In contrast with expected trends, acute altitude exposure resulted in no significant or meaningful differences in La compared to sea level tests. Following chronic high altitude exposure, however, La levels were significantly reduced at the same relative exercise intensity (85% VO_2max). Reductions in La following chronic altitude exposure were accompanied by reductions in local RPE that contributed to reductions in overall RPE despite small increases in central RPE. These results support the contention that feelings of muscular strain dominate the effort sense and peripheral factors make major contributions to RPE. Although some measures of central physiological demand increased (i.e., HR, VO_2), with accompanying small increases in central RPE, local and overall RPEs demonstrated small nonsignificant reductions at altitude. HR and VO_2 have been identified, however, as cues that are unlikely to be consciously perceived during exercise (Mihevic, 1981; Robertson, 1982). Together, these results suggest that RPE is closely aligned with perceptions of local physiological strain and peripheral parameters such as La.

Although it is generally accepted that La is an important mediator of perceived exertion, evidence exists to refute this claim. Perturbations in the RPE-La relationship have been demonstrated during repeated bouts of exercise. Weltman et al. (1998) examined the effect of sequential exercise bouts (one-hour recovery) and delayed exercise bouts (3.5 hours recovery) on RPE and La responses in moderately trained participants (*N* = 6) during 30 minutes of steady-state exercise at a power output associated with 70% of VO_2max. Mean La responses were not significantly or meaningfully different between sequential and delayed bouts, although both exercise protocols resulted in significant decreases in peak La with repeated bouts. RPE responses were not meaningfully different between the two exercise protocols, but significant increases in local and overall RPE were demonstrated with repeated bouts. The authors concluded that repeated bouts of exercise on the same day will disturb the RPE-La relationship and that RPE should not be used to prescribe exercise intensities when exercise is repeated on the same day. Other factors, however, might have influenced La and RPE responses in this study. Because participants fasted throughout the testing period, the lower La responses might be the result of depleted muscle glycogen levels (blood glucose did not vary beyond normal limits during testing). As described later in this section, the availability of energy substrates might also mediate RPE responses. The depletion of energy substrates during repeated bouts of exercise on the same day might, therefore, have different effects on RPE and La responses. These results highlight the likely influences of various systems and parameters in determining perceptual responses to exercise.

RPE and La responses between laboratory and field exercise tests have also demonstrated variations in the RPE-La relationship. Ceci and Hassmén (1991) investigated the effect of running on a track or a treadmill at certain RPEs on La. Two sessions were undertaken in which participants (*N* = 11) were asked to run at intensities associated with RPEs of 11, 13, and 15 on a treadmill and then on an outdoor running track. Significantly higher La concentrations were found during field testing compared to treadmill testing (19% to 76% greater), with differences becoming more pronounced as participants were required to reproduce higher RPEs. Running velocities and HRs were also significantly greater during field testing, suggesting that factors associated with treadmill running provide some input into the effort sense. In this study, extra demands in the laboratory setting (e.g., the self-adjust treadmill velocities using a hand-held device) might have contributed to perceptions of effort. The authors reported that this adjustment might last three-quarters of the total exercise time for each intensity. Given the participants were experienced runners and no doubt familiar with running in a field environment, differences in habituation between the two testing protocols might have contributed to higher running velocities, HRs, and La concentrations for a given RPE during track running.

In a similar study, Thompson and West (1998) determined RPEs corresponding with a 2.5 $mmol.l^{-1}$ FBLC for nine experienced runners during incremental treadmill tests. The participants ($N = 9$) were then asked to complete 30 minutes of steady-state running at the corresponding (2.5 $mmol.l^{-1}$ FBLC) RPE on an outdoor running track. Consistent with the findings of Ceci and Hassmén (1991), La concentrations were significantly higher than 2.5 $mmol.l^{-1}$ at minute-10 (6.9 $mmol.l^{-1}$), minute-20 (6.3 $mmol.l^{-1}$), and minute-30 (5.8$mmol.l^{-1}$) of the steady-state protocol. Greater running velocities during the first five minutes and higher HRs throughout the 30-minute field test again demonstrated that participants had difficulty transferring workloads associated with given RPEs between treadmill and field protocols. Potteiger and Evans (1995) reported comparable results with ten trained runners asked to replicate running intensities associated with 4.0 $mmol.l^{-1}$ FBLC (determined from a GXT) during a 5000-metre run on an outdoor track. Three field runs were performed using HR and central and peripheral RPEs to regulate running intensities. La was assessed at 1000, 3000, and 5000 metres. La was consistently higher throughout field runs regulated by RPE and HR. Again, running velocities were substantially greater during field tests, particularly during the first 2000 metres. Combined, these studies suggest that the relationship between RPE and La exhibited under laboratory conditions may not hold during field-testing. Rather than suggest, however, that RPE is not stable at certain FBLCs, it seems from these results that individuals do not process sensory information relating to physical exertion in the same way in laboratory and field testing conditions.

The transferability of the RPE-La relationship from laboratory GXTs to field steady-state tests may be protocol dependent. Moreau, Whaley, Ross, and Kaminsky (1999) compared responses from two maximal treadmill tests (Balke GXT and Bruce GXT) with responses from a steady-state treadmill test consisting of two consecutive eight minute bouts of running at 40% and 70% of maximal HR reserve. La concentrations at matched RPEs were compared between the two GXTs and the steady-state trial. La concentrations at matched RPEs during the steady-state protocol were closer to those obtained during the Bruce protocol compared to the Balke protocol. Differences were more pronounced at 70% of maximal HR reserve where the Balke protocol produced substantially lower La concentrations (1.8 $mmol.l^{-1}$) and higher RPEs (11.9) when compared to the La (3.0 $mmol.l^{-1}$) and RPE (9.6) responses obtained during the steady-state test. Both GXT protocols produced lower La and greater RPE responses when running at the same percentage of HR reserve compared to steady-state running. This result was likely due to stage durations that were too short to obtain steady-state La responses. Compared to the steady-state protocol, the 1-minute stages used in the Balke protocol produced greater differences in physiological and perceptual responses than the 3-minute stages used in the Bruce protocol. The authors concluded that GXT protocols with stage durations greater than or equal to three minutes might be necessary for establishing RPE-La relationships that are transferable to steady-state exercise training. The relationship between La and RPE, however, was not consistent between the Bruce and steady-state protocols. Other researchers have suggested that exercise periods of at least five minutes might be necessary to attain steady-state La concentrations (Foxdall et al., 1996; Foxdall, Sjödin, Sjödin, & Ostman, 1994).

Researchers investigating the effects of changing environmental temperatures on RPE have also reported inconsistencies in the RPE-La relationship. In research described in more detail in a later section on RPE and temperature, Glass et al. (1994) measured RPE, metabolic, and cardiorespiratory responses of six participants during 30-minutes of steady-state exercise at 80% of VO_2max in low (14.7°C), moderate (21.0°C), and high (27.4°C) temperatures. The authors found that RPE did not vary across the exercise conditions despite significant differences in La concentrations between conditions. Data required to calculate effect sizes were not reported, but variations in RPE at given time points were small (1% to 5%), suggesting that individuals might not perceive greater La concentrations associated with exercise in hot conditions.

In contrast to the results reported earlier that RPE is stable at LT and FBLCs regardless of state of training (Boutcher et al., 1989; Foster et al., 1999; Seip et al., 1991), Held and Marti (1999) suggested that variations in fitness level may alter the RPE-La relationship. Examining the results from incremental treadmill tests performed by 319 male and 145 female members of the Swiss Olympic team, Held and Marti compared the running performance and RPE responses of the bottom 10% and top 10% endurance trained participants at a 4.0 $mmol.l^{-1}$ FBLC. At 4.0 $mmol.l^{-1}$ FBLC the RPE responses of the fittest group were 4.3 points higher ($p < .001$) for men and 2.9 points higher ($p < .001$) for women than the least fit group. This seemingly contradictory finding can be explained by the fittest participants running at significantly faster treadmill velocities (male, 5.4 $m.s^{-1}$; female, 4.4 $m.s^{-1}$) than the least fit group (male, 2.9 $m.s^{-1}$; female, 2.6 $m.s^{-1}$;

$p < .001$) to attain La levels of 4.0 $mmol.l^{-1}$. In this study, endurance trained athletes were able to sustain much greater running velocities at 4.0 $mmol.l^{-1}$FBLCs, suggesting that RPE was more closely associated with actual exercise intensity than with La concentrations.

There is little published evidence describing the relationship between La and RPE with highly trained elite athletes. As reported earlier, Foster et al. (1999) found RPE to be stable at particular FBLCs in world-class speed skaters during in-season and off-season training, despite participants' power outputs being significantly greater during in-season training. Morgan and Pollock (1977) compared the RPE and physiological responses of world-class middle distance and marathon runners with college runners. At absolute exercise intensities that represented 84% of VO_2max in the elite group and 95% of VO_2max in the college group, RPE and La concentrations were both significantly lower in elite level runners.

Overall, the results presented in this section suggest that La and RPE are associated across a variety of testing conditions. The close relationship between La and RPE may be stronger at workloads above the LT (Kolkhorst et al., 1996; Spodaryk, Szmatlan, & Berger, 1990; Steed et al., 1994). More specifically, the LT appears to be an important junction for RPE responses. Training induced increases in workloads associated with the LT have been shown to have little influence on RPE responses at the LT (Boutcher et al., 1989; DeMello et al., 1987). The stability of RPE responses at the LT have also been demonstrated with elite athletes across trained and detrained periods of the athletic season (Foster et al., 1999). Consistent with the proposal that RPE responses are determined by multiple physiological mediators, some study results have suggested that RPE is not stable at LT and FBLCs and might be more closely associated with ventilatory parameters (Haskvitz et al., 1992) or absolute exercise intensities (Held & Marti, 1999). Experimental evidence shows that the RPE-La relationship might be disturbed under some conditions.

Researchers have reported that pedal rate (Löllgen, 1980), repeated exercise bouts (Weltman et al., 1998), laboratory and field testing (Ceci & Hassmén, 1991), and oxygen availability (Pedersen & Welch, 1977) might alter the relationship between La and RPE. Despite inconsistencies in research results, most researchers have suggested that La is an important mediator of RPE, particularly at higher exercise intensities where La concentrations contribute to muscular fatigue and provide a greater input to the perception of effort.

pH

Some of the effect of La on RPE at intensities higher than the LT may be the result of decreased pH in working muscles. Increases in La production and H^+ concentrations associated with high intensity exercise result in reductions in pH. Combined, these effects inhibit the activity of glycolytic enzymes, interrupt ATP production, and reduce the ability of muscle fibres to contract (Sutton, Jones, & Toews, 1981). The resultant muscular fatigue increases motor unit recruitment and firing frequency (Kostka & Cafarelli, 1982) resulting in increases in peripheral signals of exertion (Robertson et al., 1986), which are, in turn, monitored by the sensory cortex (McCloskey, Gandevia, Potter, & Colebatch, 1983). Central signals of RPE are also accentuated by low blood pH because respiratory compensation for metabolic acidosis results in V_E increasing disproportionately with workload (Ehrsam, Heigenhauser, & Jones, 1983; Robertson et al., 1988). The interconnectedness of metabolic systems during exercise makes it difficult to distinguish the relative contribution of V_E, pH, and La on RPE. Further confounding these relationships are the independent effects of La and pH on RPE under induced alkalosis. The relatively alkaline environment caused by $NaHCO_3$ ingestion results in a prolonged glycolytic production of ATP and increases in La (Sutton et al., 1981). Induced alkalosis has been shown to reduce peripheral perceptions of exertion at higher exercise intensities despite higher La levels (Robertson et al.).

Robertson et al. (1986) investigated the effect of induced alkalosis on RPE during arm, leg, and combination arm and leg exercises. Ten active male participants performed each of the three exercise modes 12 hours following $NaHCO_3$ and $CaCO_3$ (placebo) ingestion. Each trial was separated by seven days and consisted of three-minute stages of progressive, incremental exercise with power outputs equivalent to 20%, 40%, 60%, and 80% of ergometer specific VO_2max. Arm, leg, chest, and overall RPE were measured upon completion of each workload. HR and ventilatory variables were recorded every minute of exercise and blood samples were drawn prior to ingesting experimental substances, immediately prior to commencing exercise, and immediately following the final workload. At 20%, 40%, and 60% of VO_2max, RPEs did not differ between experimental conditions. At 80% of VO_2max, however, all RPE measures were lower following $NaHCO_3$ ingestion compared to the placebo condition during all exercise trials. Of the physiological variables, V_E and RR exhibited similar changes and were significantly different at 80% of VO_2max, whereas negligible differences were reported for HR, tidal volume, and VO_2 at any exercise intensity. Blood pH was significantly higher prior to exercise and at 80% VO_2max following $NaHCO_3$ ingestion. The authors concluded that acid-base shifts mediate perceptions of exertion at higher exercise intensities. In addition, greater RPE responses under metabolic acidosis at high exercise intensities are, in part, mediated by V_E.

Robertson et al. (1992) also demonstrated the mediating effect of pH on perceptions of exertion during recovery. Participants ($N = 9$) were randomly presented with four maximal treadmill protocols at constant speeds where treadmill grade was increased 2%, 4%, 6%, or 8% every three minutes. Exercise tests continued until voluntary exhaustion, upon which participants were instructed to rest in a supine position for 12 minutes. Leg, chest, and overall RPEs and cardiorespiratory variables were recorded upon completion of each exercise trial and every minute during post-exercise recovery. Blood samples were taken immediately prior to exercise, upon termination of exercise, and after 6 and 12 minutes of recovery. All RPE measures, RR, and V_E were significantly greater, and pH was significantly reduced during recovery following the 8% graded protocol compared to the 2% graded protocol. Post-exercise increases in leg and overall RPE followed reductions in blood pH. A similar relationship was reported between chest RPE and V_E and RR. During recovery, the perceptual signal strength for localised leg ratings was greater than chest ratings, resulting in the pattern of change in overall RPE following changes in leg RPE and reductions in pH. The authors reported that it is likely that the residual effects of metabolic acidosis contributed to leg pain and discomfort during recovery, and these sensations dominated post-exercise overall RPE responses.

Swank and Robertson (1989) examined the effects of alkalosis on RPE responses during high intensity intermittent exercise with six endurance-trained women. The exercise trials involved three 5-minute bouts of cycling at 90% of VO_2max separated by 10 minutes of rest. Exercise was performed in three experimental conditions: $CaCO_3$ (placebo), $NaHCO_3$ ingested as a single dose two hours prior to exercise, and $NaHCO_3$ ingested on a periodic schedule (40% two hours prior to exercise and the remaining 60% administered equally between exercise bouts). Blood samples were drawn, and pH and bicarbonate concentration were measured prior to substance ingestion, immediately prior to each exercise bout, and five minutes following each exercise bout. Chest, legs, and overall RPEs (CR-10) were assessed in the last 20 seconds of each exercise bout. When compared to the placebo condition, single and periodic $NaHCO_3$ conditions elicited significant increases in pH and bicarbonate at all test points, with the single dose conditions resulting in larger increases in pH and bicarbonate following exercise bouts. When averaged across all test points, RPEs were significantly reduced following periodic and single dose $NaHCO_3$ ingestion when compared to the placebo trial. In concert with acid-base measures, the single dose trials resulted in larger decreases in RPE. Although chest RPE was significantly reduced under alkolitic conditions, it was not related to an attenuation of V_E, which showed little difference between conditions. Multiple regression analyses revealed significant correlations between bicarbonate and leg ($r = -.88$), chest ($r = -.89$), and overall ($r = -.86$) RPEs, but no significant correlations between pH and perceptual responses (the magnitude of these correlations were not reported). The measurement of bicarbonate concentration is a more direct measure of the H^+ buffering capacity in blood than relative pH concentrations, and may be a more relevant correlate of perceptions of exertion. Although this study supports the contention that $NaHCO_3$ ingestion and the resultant increases in blood pH and bicarbonate concentrations are associated with an attenuation of RPE, the small and homogenous sample makes the generalisation of these results difficult.

The results of some studies bring into question the role of pH in mediating perceptions of exertion. Kostka and Cafarelli (1982) did not demonstrate significant alterations in perceptual responses during 30 minutes of exercise (15 minutes at 50% and 15 minutes at 80% of VO_2max) following $NaHCO_3$ ingestion (alkalosis). Following NH_4Cl ingestion (acidosis), however, significant increases in perceptions of exertion were reported. Differences in cardiorespiratory variables were reported only for the acidosis condition at the higher intensity. In contrast to Robertson et al. (1986), these results suggest that alkolitic shifts in pH do not affect perceptions of exertion. Kostka and Cafarelli, however, induced a .04 change pH in the alkolitic condition, whereas the change reported in the Robertson et al. study was .10. In the acidosis condition, which did result in alterations in perceptual responses, Kostka and Cafarelli reported a .16 change in pH.

Combined, these results suggest that a shift in pH of less than .10 may be insufficient to affect perceptual responses to exercise. Swank and Robertson (1989) presented results that draw into question this contention and reported significant reductions in RPEs following intermittent $NaHCO_3$ ingestion that resulted in shifts in pH of less than .10.

Robertson et al. (1979) examined RPE responses from 50 participants during submaximal cycle ergometer work at the same absolute workload, but with varying pedal frequencies (40, 60, and 80 rpm). Lower pedal frequencies were associated with higher RPEs and central indicators of exertion. The authors did not report significant differences in La or pH between pedal frequencies and concluded that measures of anaerobic metabolism were similar across experimental conditions. Acid-base alterations showed, however, that pH was .13 lower in the 80 rpm condition compared to the 40 rpm condition. As reported above, changes in blood pH greater than .10 have previously been sufficient to induce alterations in RPE (e.g., Robertson et al., 1986). These results suggest that alterations in pH may have mediated RPE responses.

In general, there appears to be some influence of blood pH on perceptions of exertion, but this effect may only emerge at higher exercise intensities and only when pH has been altered sufficiently. Because the research presented uses venous blood to measure pH, the proposed dependent relationship between pH and RPE presupposes that shifts in blood pH reflect changes in muscle pH. The effects of pH on RPE during exercise are integrated with other measures of anaerobic metabolism (e.g., La) and associated respiratory responses. The integration of such systems involved in meeting metabolic demands during exercise means that overall perceptions of exertion are likely to result from a gestalt of physiological mechanisms.

Muscle Fibre Type

There is strong theoretical and indirect empirical evidence that the relative percentage of fast-twitch (FT) and slow-twitch (ST) muscle fibres has a mediating role in the perception of effort. Tesch, Sjödin, and Karlsson (1978) reported greater concentrations of La and H^+ in FT compared to ST muscle fibres during high intensity exercise, and Noble et al. (1983) reported that muscular fatigue and metabolic acidosis occurred earlier in muscles rich in FT, compared to ST fibres. For FT muscle fibres to overcome muscular fatigue and maintain the force of muscular contractions, increases in efferent neural impulses from the central nervous system are needed. This increase in neural activity leads to more intense signals of exertion from FT compared to ST muscle fibres (Noble & Robertson, 1996).

Although theory supports a link between RPE and muscle fibre composition, there is little supporting research. Ljunggren et al. (1987) reported perceptual and physiological responses from 22 healthy male participants cycling for 15 minutes at a power output equivalent to La concentrations of 4.0 $mmol.l^{-1}$. Participants were grouped according to La accumulated at minute-15 of exercise, and responses were compared between participants with elevated (n = 7), intermediate (n = 8), and low (n = 7) rates of La accumulation. Although the authors reported that differences in the rate of La accumulation between groups might have been a result of differences in the relative percentage of muscle fibre composition (in vastus lateralis), the results presented do not support this claim. The moderate to very large differences in muscle fibre composition between the groups (d = 0.49 to 1.21) did not follow expected trends. The group with elevated La concentrations exhibited a higher percentage of ST fibres (M = 49.0, SD = 10.7) compared to the group with low La levels (M = 44.0, SD = 9.9). There were no significant differences in RPE between groups, and the order of magnitude for RPE responses did not follow expected trends according to La accumulation or muscle composition. Conclusions made in this study relating the relative percentage of ST and FT muscle fibres with La accumulation and RPE are further cast into doubt because only 12 of 22 participants had their muscle composition measured, yet the La responses from all 22 participants were used to differentiate between groups. This anomaly resulted in one group with only two participants providing their relative muscle fibre types. The decision to trichotomise a continuous variable (accumulated La at minute-15) to determine groups also brings into question the reliability of these results.

Noble et al. (1983) presented research findings that demonstrated a strong relationship between perceived exertion (CR-10 scale) and blood and muscle La. The authors also measured participants' ($N = 10$) muscle fibre composition (vastus lateralis) and compared perceptual responses between participants with the highest ($M = 51.14$) and lowest ($M = 34.52$) percentages of ST fibres. The group with the lowest percentage of ST fibres reported significantly greater peripheral and central perceptions of exertion compared to the group with the highest percentage of ST fibres. Although these results support theoretical expectations, the use of a median split to distinguish participants high and low in ST fibres limits these findings. Generally, one should not dichotomise (or trichotomise, as done by Ljunggren et al., 1987) a continuous variable (Cohen, 1983, 1990), and certainly not with only 10 participants.

Löllgen et al. (1980) did not find supporting evidence for a relationship between perceptions of exertion and the relative percentage of FT and ST muscle fibres. Participants ($N = 6$) performed repeated bouts of cycling at constant power outputs, but with variations in pedal frequency. Although the authors reported a strong correlation between La accumulation and percentage of ST muscle fibres ($r = .91$), they did not demonstrate a significant relationship between these variables and RPE. The lack of relation between La and RPE contradicts theoretical expectations and other experimental research findings. The authors, however, did not report the size of the nonsignificant correlations of RPE with La and percentage of ST fibres. Detecting significant relationships with such a small sample size would require an extremely large effect.

Although there is a theoretical argument underlying the proposed link between muscle fibre composition and perceptions of effort during high intensity exercise, little direct evidence is available supporting this contention. Further research is needed that more directly examines the relationship between muscle fibre composition and perceptions of effort. Some of the methodological and analytical limitations in the research presented in this section arise because the studies were not designed specifically to examine the relationship between muscle fibre composition and RPE.

Muscle Blood Flow

Research findings have suggested that vascular occlusion shortens the time to exhaustion during physical work, with this effect being more pronounced during low force contractions over longer time periods (Humphreys & Lind, 1963; Start & Holmes, 1963). Similarly, increased ratings of pain have been reported during exercise performed when blood flow to working muscles was restricted (Caldwell & Smith, 1966). Other researchers have demonstrated that the ability to maintain a constant force of contraction over time is truncated by vascular occlusion, but only beyond the first minute, after which the force of contraction drops rapidly (Stephens & Taylor, 1972).

The effect of restrictions to muscle blood-flow on perceptions of exertion and fatigue have been demonstrated using isometric (static) muscle contractions to alter blood circulation. Sustained muscle contractions involved in isometric work restrict blood flow to working muscles (Asmussen, 1981) and result in compensatory increases in arterial blood pressure (Seals, Chase, & Taylor, 1988). Stephens and Krimsley (1977) had 20 young men reproduce the same perceived effort during repeated multiple hand-grip contractions. When blood flow was occluded, the number of contractions required to reproduce the same subjective effort decreased, but only in work bouts requiring 10 contractions or more. In separate trials, five participants performed constant effort, sustained, isometric hand-grip contractions and repeated multiple hand-grip contractions under conditions of venous occlusion and non-occlusion. Consistent with other research (Cain & Stevens, 1973; Pandolf & Cain, 1974), isometric contractions, independent of venous occlusion, resulted in a rapid reduction in the force needed to maintain constant perceived effort compared to repeated multiple hand-grip contractions. Occlusion, however, had a strong influence on fatigue during repeated contractions. After approximately one minute of work venous occlusion resulted in a dramatic reduction in the force required to maintain constant perceived effort, whereas under normal conditions, the force generated to maintain a constant perceived effort slowly decreased over time.

The link between interruptions in blood flow to working muscles and elevations in RPE may be associated with a restriction of the energy substrates and oxygen delivered to active muscles (Noble & Robertson, 1996). When exercise demands require a high percentage of maximum voluntary contraction, parts of the vasculature are mechanically restricted (Asmussen, 1981). This restriction results in reductions in the tissue perfusion of blood, occluding the delivery of energy substrates and oxygen to active muscles and intensifying peripheral exertional signals (Noble & Robertson, 1996). An interruption of blood flow to active muscles increases anaerobic glycolysis, accelerates metabolic acidosis and muscle fatigue and results in increases in local signals of exertion.

Energy Substrates

Researchers have suggested that the availability of glucose and free fatty acids (FFA) in circulating blood mediate perceptions of exertion during prolonged submaximal exercise (Burgess, Robertson, Davis, & Norris, 1991; Dohm, Beeker, Israel, & Tapscott, 1986). Under some exercise conditions, however, blood levels of glucose and FFA covary, making the determination of their independent effects on perceptions of exertion problematic (Noble & Robertson, 1996). The most effective method to determine the influence of energy substrate availability on RPE is to manipulate each substrate separately. Researchers have employed carbohydrate (CHO) supplementation to manipulate glucose availability (Utter et al., 1999) and caffeine supplementation to manipulate FFA availability (Bell, Jacobs, & Zamecnik, 1998) and examined the effects on RPE.

Low levels of glucose in circulating blood have been shown to limit endurance capacity (Coggan & Coyle, 1987; Coyle, Coggan, Hemmert, & Ivy, 1986). Muscle glycogen is the primary source of energy at the beginning of exercise and blood glucose meets about 40% of the energy requirements from 10 to 40 minutes beyond the commencement of exercise (Van De Graaf & Fox, 1989). As exercise continues, and blood glucose declines, there is an increasing reliance on muscle glycogen stores to fuel exercise demands. Over time, the depletion of CHO (carbohydrate) fuel sources gives rise to muscular fatigue and limits endurance performance. The most obvious mechanism by which CHO availability affects RPE is that CHO depletion leads to a disruption in the contractile properties of skeletal muscle. The depletion of muscle glycogen stores following prolonged exercise leads to an interruption in energy supply for muscle fibre contraction. To fulfil exercise demands more motor units are recruited and firing frequency increases leading to local muscular fatigue. These alterations require an increase in feedforward signals from the central motor cortex. These signals lead to an accompanying increase in corollary discharge signals to the sensory cortex resulting in more intense exertional signals. An alternative suggestion is that glucose is an important substrate for the central nervous system. During prolonged submaximal exercise, reductions in available glucose may disrupt central nervous system function, alter the final common pathway for sensory and motor signals, and intensify perceptions of exertion.

A number of more recent research findings have supported the role of blood glucose availability in mediating perceptions of effort during prolonged endurance exercise. Utter, Kang, Nieman, and Warren (1997) manipulated CHO metabolism by having marathon runners ingest either a CHO solution (n = 17) or a placebo (n = 13) half an hour prior to, and every 15 minutes during two and a half hours of running at 75-80% of VO_2max. After 100 minutes of exercise, the CHO group exhibited significantly lower RPEs compared to the placebo group. Cumulative CHO oxidation between groups diverged over time and was significantly greater in the CHO group after 140 minutes of exercise, as was post exercise blood glucose levels. Fat oxidation was significantly lower in the CHO group after 120 minutes. RR and respiratory exchange ratios were consistently higher following CHO supplementation. This effect is possibly connected to increased CHO oxidation, and suggests that increased CHO availability attenuates perceptions of exertion despite the stimulatory effect CHO supplementation has on V_E. The authors concluded that during the latter stages of prolonged submaximal exercise, the availability of CHO mediates the intensity of exertional perceptions. Employing similar experimental protocols using within-groups designs, other researchers have presented comparable results during two (Kang et al., 1996) and three hours of cycling (Burgess et al., 1991).

Robertson et al. (1990) used dihydroxyacetone and sodium pyruvate (DHAP) ingestion to increase the fractional extraction of blood glucose during arm-crank exercise at 60% of VO_2max to voluntary exhaustion in eight participants. After 60 minutes of exercise, arterial-venous glucose differences and muscle glycogen concentration were significantly higher in the DHAP trial compared to placebo, but the differences were negligible for La and pH. RPE-chest and RPE-legs did not differ between trials, but by 60 minutes, RPE-arms and RPE-overall were significantly lower for the DHAP trial. The authors reported that increases in arterial-venous glucose extraction during the DHAP trial, without accompanying increases in blood flow to the arm, was likely to have occurred because of enhanced muscle glucose uptake during prolonged exercise. The authors suggested that attenuations in RPE-arms during the DHAP trial might have been the result of greater uptake of glucose from working muscles.

Okano et al. (1988) did not report an attenuation of RPE responses during prolonged submaximal exercise following fructose ingestion compared to a placebo trial for 12 trained participants. Despite significantly increased time to exhaustion (132 to 145 minutes), fructose supplementation had no meaningful effect on RPE. Although other researchers have demonstrated changes in blood glucose and CHO oxidation following CHO supplementation (Burgess et al., 1991; Kang et al., 1996; Utter et al., 1997; Utter et al., 1999), Okano et al. did not report changes in serum glucose levels during exercise. This difference may be the result of not providing CHO supplementation during exercise. Also, unlike the participants from the previous research who fasted for 12 hours prior to exercise, the participants in the Okano et al. study consumed controlled meals up to four hours prior to the placebo and experimental trials.

Research evidence does not generally support a role for FFAs and glycerol in mediating perceptions of exertion during long or short-term exercise. Bell et al. (1998) investigated the effects of caffeine and adrenaline ingestion on physiological and perceptual responses during short-term exercise. FFA concentration was significantly elevated during the caffeine trial compared to the placebo trial. There were no significant or meaningful differences, however, in ventilatory variables or RPE between the caffeine and placebo trials, despite caffeine ingestion increasing time to exhaustion by 15%.

Trice and Haymes (1997) examined the effect of caffeine ingestion on eight trained participants during long-term exhaustive exercise. Participants ingested caffeine one hour prior to completing 30-minute bouts of intermittent cycling at 85-90% of VO_2max. With five minutes of rest between bouts, exercise was terminated when participants could no longer maintain required power outputs. FFA serum concentration and time to exhaustion were significantly greater during the caffeine trial compared to the placebo trial. The authors reported no significant differences, however, in RPE following caffeine ingestion. The small sample size and differences in mean RPE responses of 9% (placebo RPE 17.6, caffeine RPE 16.2), which approached significance ($p = .07$), increased the likelihood of a Type II error when interpreting this result. Similarly, Okano, Sato, and Murata (1998) did not report alterations in RPE during prolonged submaximal exercise following the consumption of a high fat meal, despite increases in FFA serum concentrations and fat oxidation rates. Research describing the effects of fasting on exercise performance have also not supported serum FFA concentration as a mediator of exertion. Despite fasting increasing FFA concentrations in blood, participants performing prolonged submaximal exercise reported higher RPEs compared to control trials (Dohm et al., 1986; Nieman, Carlson, Brandstater, Naegele, & Blankenship, 1987).

Some researchers, however, have demonstrated an attenuation in perceptions of exertion with increases in FFA concentration following caffeine ingestion. Costill, Dalsky, and Fink (1978) reported that caffeine ingestion one hour prior to exhaustive exercise increased plasma triglyceride levels, lipid metabolism, and time to exhaustion, and reduced RPE. The authors commented that reductions in feelings of strain and increases in endurance performance following caffeine ingestion were likely the result of increased lipolysis and the effects of caffeine on nerve impulse transmission. Casal and Leon (1985) reported similar results with trained marathon runners who exhibited higher serum FFA concentrations and reduced RPE responses during submaximal endurance running one hour following caffeine ingestion. The authors also reported that the effects of caffeine on muscle fibre innervation might explain reductions in RPE. Caffeine lowers the threshold for muscle fibre recruitment and nerve transmission (Waldeck, 1973), and resultant alterations in muscle fibre contractility might attenuate feelings of strain independent of direct metabolic stimulus.

Theoretical rationales do not support a direct link between lipolysis and RPE. FFA concentrations in plasma are rarely depleted to an extent where they might trigger fatigue. Rather, increases in FFA concentration are likely to affect RPE by sparing reserves of CHO. Comparatively greater concentrations of FFA decrease the reliance on CHO as an energy source, helping prolong exercise (Essig, Costill, & Van Handel, 1980) and potentially reduce perceptions of exertion.

RPE and Training

Research investigating the effect of training on RPE has included variations in testing procedures, the kinds of variables examined, and the relative fitness of participants. The variety of research protocols used to explore how training influences RPE relationships make comparisons between research results problematic. Given such variations, it is not surprising that research examining the effect of training on RPE relationships has produced equivocal findings.

Investigations of training-RPE relationships have commonly tested participants at absolute exercise intensities. Absolute exercise intensity refers to a fixed exercise workload that is not connected to an individual's work capacity. Examples of absolute exercise intensities used in RPE research include running at 10 mph, cycling at 250 W, or walking on a graded treadmill until HR reaches 180 bpm. Comparing the perceptual responses of participants at absolute exercise intensities, however, appears incongruous with the premises on which the RPE scale was developed. Underlying the development of the RPE scale was the concept that an individual's perceptual range can be set equal for all people. That is, the top and bottom of the perceptual range are equal because no exertion and maximum exertion are perceived as the same for everyone. The absolute exercise intensities at which these points fall, however, will be different. For example, maximum exertion for an elite cyclist will occur at a much higher power output than for a sedentary person. The same absolute exercise intensities will, therefore, represent greater relative physiological demand (e.g., percentage of VO_2max) for less fit individuals compared to their fitter counterparts and will occur higher on the perceptual range for less fit participants. Cycling at a power of 200 W will be closer to the maximum perceptual response (i.e., RPE of 20) for a sedentary participant compared to an elite cyclist. Although Borg (1998) suggested that RPE should relate well to absolute measures of exercise intensity, RPE is more closely associated with measures corrected for individuals' work capacities.

Research Using Absolute Workloads

Research findings generally demonstrate that RPEs are lower in trained participants at absolute exercise intensities, although these results appear to be protocol dependent. Given the perceptual range basis for the development of the RPE scale, these results are not surprising. RPE is likely to be lower at absolute exercise intensities for trained participants because these intensities represent less relative physiological demand and occur lower on the individual's perceptual range. Such comparisons simply describe how training can lower the perceptual range of participants relative to an absolute stimulus.

Hassmén (1990) compared RPE responses of "specialised" athletes (trained cyclists, $n = 6$ and runners, $n = 6$) with "non-specialised" athletes (all-round trained, $n = 6$) and sedentary individuals ($n = 6$) in running and cycling GXTs using 4-minute absolute workloads. HRs and RPEs were reported as higher in the sedentary group compared to the trained groups at sub-maximal and maximal exercise workloads. Sedentary participants also accumulated La much earlier than the trained groups, with onset of blood lactate accumulation (4.0 $mmol.l^{-1}$) occurring at a lower workload in the sedentary group. These results demonstrate that trained individuals are under less physiological strain compared to untrained individuals at absolute workloads, and perceived less exertion at these workloads. "Specialised" athletes also tended to exhibit less physiological demand and lower perceived exertion in their specialised sports. These expected results, however, explain little of how training affects the relationship between physiological mediators of exertion and RPE because the relative physiological demand placed on participants varied according to their level of fitness.

Morgan and Pollock (1977) compared RPE responses of world class middle-long distance ($n = 11$) and marathon runners ($n = 9$) with university runners ($n = 9$) at absolute running velocities. HRs, ventilatory responses, and RPEs were recorded every two minutes as participants ran at 10 mph for six minutes, then at 12 mph for a further six minutes. Despite significantly lower HRs and percentage of VO_2max for the world class groups when running at 10 mph, there were no significant differences in RPEs between groups. Running at 12 mph, however, the world-class runners exhibited significantly lower RPEs, HRs, and percentage of VO_2max than the university runners. The authors suggested that the differences between the groups in RPE during high intensity, but not low intensity exercise, may be attributable to the onset of anaerobiosis in the university runners. This suggestion is understandable given the university runners exhibited significantly higher La levels and were working at 95% of VO_2max compared to 84% of VO_2max in the world class runners. Correlations between RPE and physiological variables were calculated and suggest that La ($r = .61$) and V_E ($r = .65$) were major contributors to RPE. The importance of using relative physiological demand, rather than absolute exercise intensity, when comparing RPE responses is highlighted by the finding that differences in RPEs between marathon and college runners were dependent on exercise intensity.

Patton, Morgan, and Vogel (1977) examined RPE and HR responses during a six-minute run at an absolute workload of six mph in two groups of 60 military personnel. Baseline cross-sectional comparisons were made between participants not engaged in a training program (group 1) and a group who had engaged in five months of endurance training (group 2). A second test was performed six months later at time 2, with both groups having participated in endurance training, group 2 for 11 months and group 1 for the six months. At time 2, change scores were analysed from results obtained at baseline. Between group comparisons at baseline demonstrated that the endurance trained group had significantly lower HRs at each minute of exercise, but there were no difference in RPEs compared to the untrained group. These cross-sectional comparisons appear to contradict the findings reported earlier and suggest that absolute workloads are not perceived as any more strenuous by untrained participants compared to trained participants, despite the untrained group working at a higher physiological demand. Some methodological and interpretation issues exist, however, that may affect the validity of these results. First, although the difference in fitness between the groups at baseline was significant, this contrast only represented a 10% difference in maximal aerobic power. Further, the significant difference in HR reported at baseline represented only a 5% difference between the groups. It could be expected that such a small difference in physiological demand might not result in any difference in RPE, especially given the low intensity and short duration of exercise testing. These results suggest a strong possibility of misinterpreting differences in baseline HRs and initial fitness levels between groups. Second, relative exercise intensities used during the exercise tests at baseline represented only 81% (group

1) and 75% (group 2) of participants' VO_2max. These intensities may not be sufficient for metabolic acidosis and associated variables to make major contributions to RPE. Other researchers have demonstrated differences in RPE between groups of varying fitness at high, but not low or moderate exercise intensities (Morgan & Pollock, 1977; Spodaryk et al., 1990).

Change score comparisons performed at time 2 for the six month trained group appear to offer conflicting results to between group comparisons performed at baseline. At time 2, both groups had significantly lower HRs (10% for group 1, 5% for group 2) and RPE (11% for group 1, 13% for group 2) when compared longitudinally with baseline responses. In contrast with the between groups comparisons made at baseline, these within groups comparisons suggest that training lowers both HR and RPE at given workloads. One weakness in this study is that there was no control group with which to compare results. The participants in this study may have responded to the demand characteristics of exercise training and testing, and the participants may have expected to perceive exercise as less demanding following training and responded accordingly. Morgan, Patton, Vogel (1977) also noted that group 2 decreased their HR, VO_2, and RPE at time 2 despite no changes in VO_2max. These results may indicate a degree of habituation by participants to exercise demands that is reflected in lower physiological and perceptual responses to workload. Psychological adjustment to strenuous exercise may contribute to elite athletes perceiving increased physiological exertion as no less demanding.

Mihevic (1983) investigated the RPE and HR responses of 34 male and 41 female participants classified as high or low fit on the basis of their VO_2max. Employing a variety of submaximal exercise intensities (200, 400, 800, and 1000 $kpm.min^{-1}$) of six-minute duration, Mihevic reported that RPE responses were not significantly different between the high and low fit groups at any intensity, despite significantly higher HRs for the low fit participants at all exercise intensities. An examination of effect sizes, however, indicated a moderate to large difference in RPE between high and low fit men (f = .30), and extremely large differences in HR (women, f = 1.14; men, f = 1.34). These results do not follow theoretical expectations, although methodological issues may have influenced these results. Similar to Patton et al. (1977), exercise intensities employed during testing in this study were not likely to exceed 80% of VO_2max for the low fit participants. Mean HRs for the low fit group did not exceed 170 bpm for women and 150 bpm for men. Thus, test exercise intensities may not have presented sufficient physiological demand to distinguish between the perceptual responses of high and low fit participants. Mihevic concluded that the RPE scale does not discriminate between high and low fit participants during short term, low to moderate intensity exercise, despite differences in cardiovascular strain. This result is consistent with other research findings that suggest RPE may not provide a practically useful way of evaluating exercise intensity until important mediators of RPE, such as La and V_E, increase substantially in response to metabolic acidosis (Robertson et al., 1986; Seip et al., 1991).

Morgan (1977) measured HR and RPE responses during five-minute constant load exercise tests with US Olympic freestyle wrestling candidates. Athletes who made the team (fit group) were compared with athletes who did not make the team (less fit group). HRs for the fit group were significantly lower at every minute of exercise, whereas RPE responses were similar across the duration of the test. Methodological flaws similar to Patton et al. (1977), however, limit this study. Again, significant differences in fitness levels were reported between the groups, but these differences represented less than a 10% difference in VO_2max. This highlights the questionable assertion that successful and unsuccessful Olympic wrestling candidates would necessarily differ in fitness. Althletes make teams based on a lot of other things than fitness (e.g., skill). Also, mean HR for the "less fit" group at the fifth minute of exercise was approximately 140 bpm. This level of cardiovascular demand would be unlikely to be sufficient to make distinctions in RPE between groups of varying fitness. Finally, Morgan does not identify how many participants were in each group. Depending on group size, both Type I and II errors were possible when interpreting HR and RPE differences, respectively.

Sidney and Shephard (1977) investigated the effects of a 34-week aerobic conditioning program on a group of 60 to 70 year old participants ($N = 23$). The program significantly improved indices of fitness for the participants, representing a 17% (males) and a 25% (females) improvement in VO_2max. Despite exercise testing indicating a significant reduction in HRs at absolute workloads (up to 85% of maximal output) from pre- to post-program, there was little effect on perceptions of effort. Again, testing exercise intensities may not have been sufficient to affect RPE. Although reductions in HR were reported as significant, they only represented a change of 6% in men and 4% in women.

Results from research employing absolute exercise intensities to determine the effect of training on RPE have generally demonstrated that trained individuals exhibit less physiological strain and subsequently perceive less exertion at absolute exercise workloads than untrained individuals. Some research findings have demonstrated no changes in RPE between groups of varying fitness at absolute exercise intensities, but these studies have often used low exercise workloads during testing. Exercise intensities below La thresholds may not provide sufficient physiological demand to detect differences in perceptions of exertion between high and low fit participants. The conclusion that trained people are less physiologically stressed, and thus perceive less exertion than untrained or sedentary people at absolute exercise intensities, is consistent with theoretical expectations. Comparing individuals at absolute intensities, however, does little to describe how the *relationship* between RPE and physiological parameters is affected by training because the relative physiological demand elicited by absolute workloads differ between participants of varying fitness. Results from such comparisons simply demonstrate how the perceptual range for perceived exertion changes in relation to physiological stimulus as a function of fitness. The influence of training on the relationship between physiological variables and RPE is better examined when participants are compared at relative workloads that are adjusted according to an individuals' exercise capacity.

Research Using Relative Workloads

Researchers examining the effects of training on RPE relationships at relative exercise intensities have compared RPE responses mostly at percentages of cardiorespiratory capacity (%VO_2max or ventilatory thresholds) and/or at the LT or FBLCs. Investigations of RPE relative to La concentrations suggest that RPE remains stable at a given La concentration irrespective of fitness (Foster et al., 1998). At exercise intensities set as a percentage of $\dot{V}O_2$max and relative to individuals' ventilatory threshold, research findings have suggested that RPE remains stable (Hill et al., 1987) or decreases (Spodaryk et al., 1990) at a given percentage of VO_2max following training.

The rate of La accumulation during exercise is closely linked to the fitness level of an individual; less fit people accumulate La faster and begin to accumulate La at lower workloads than fit people. At a La concentration of 2.0 $mmol.l^{-1}$, or at an individual's LT, a fit person will be working at a greater workload than a less fit person. In this regard, comparing people of different fitness at workloads associated with La accumulation will make some adjustment for differences in maximal exercise capacity. Because La is a major cue for RPE, and the production and removal of La is linked to other mediators of RPE, such as blood pH, HR, and V_E, FBLCs and LTs provide valuable points for comparing RPE responses to exercise.

Seip et al. (1991) compared the RPE and physiological responses of runners (n = 20) and nonrunners (n = 29) at treadmill velocities associated with the LT and FBLCs (2.0, 2.5, and 4.0 mmol.l^{-1}). Participants completed an incremental horizontal treadmill walk/run to exhaustion. Treadmill velocities increased 10 m.min^{-1} every three minutes, and initial velocities for runners (150 m.min^{-1}) and nonrunners (90 m.min^{-1}) varied so that exercise time was approximately equal. Results showed that runners exhibited significantly greater treadmill velocity, HR, VO_2, V_E, and respiratory effort at velocities associated with the LT and all FBLCs. Despite the greater physiological demand for nonrunners, central, local, and overall RPE remained the same at the LT and FBLCs. It is somewhat surprising that, irrespective of higher absolute and relative VO_2 and V_E, central RPEs at the LT and FBLCs were not significantly different between runners and nonrunners. Closer examination of the RPE data, however, indicated small to moderate increases in central RPE at 2.5 (d = .34, 13% difference) and 4.0 mmol.l^{-1} (d = .46, 18% difference) La concentrations between runners and nonrunners. Differences in RPE responses at higher workloads are consistent with the findings of other researchers who have suggested that respiratory-metabolic signals of exertion become more important at higher workloads (Cafarelli & Noble, 1976; Robertson et al., 1986). Given the tendency for increased central RPE at higher workloads between runners and nonrunners, the authors' conclusion that ventilatory cues may not be primary contributors to RPE appears questionable. The stability of local and overall RPE between runners and nonrunners at given La concentrations, however, suggests that La is a major cue for perceptions of exertion.

In one of the few studies to test RPE relationships using elite level athletes, Foster et al. (1998) examined the exercise responses of 13 speed skaters from US national teams during deconditioned (spring) and conditioned (autumn) phases of training. Testing involved an incremental cycle ergometer test with an initial power of 0.75 W.kg^{-1}, with increases of 0.75 $W.kg^{-1}$ every five minutes. Measures of HR, La, and RPE (CR-10) were taken at baseline and upon completion of each stage, and this part of the test was terminated when RPE was greater than five. After a 10-minute rest period, participants performed a 3km (females) or a 5km (males) time trial and were instructed to complete the trial as fast as possible. Physiological variables were recorded upon completion of the test when RPE was assumed to be maximum (10). Outcomes from this testing protocol previously demonstrated a close relationship to competitive performance results. HR, power output, and RPE were compared at La concentrations of 2.5 $mmol.l^{-1}$, 4.0 $mmol.l^{-1}$, and maximum. Power output increased significantly from deconditioned to conditioned phases of training at 2.5 $mmol.l^{-1}$ (28%), 4.0 $mmol.l^{-1}$ (7%), and maximum (7%). There were no significant or meaningful changes, however, in HR or RPE at 2.5 $mmol.l^{-1}$, 4.0 $mmol.l^{-1}$, and maximum. These results suggest that the perception of exertion for elite athletes is closely linked to HR and La, independent of state of training or absolute workload.

Haskvitz et al. (1992) investigated the effect of intensity of training on RPE relationships. RPE and VO_2 responses at the LT, FBLCs (2.0, 2.5, and 4.0 $mmol.l^{-1}$) and peak were compared between sedentary controls ($n = 7$), a LT trained group ($n = 9$), and a >LT trained group ($n = 9$). The LT group trained for one year at training velocities associated with their LT. The >LT group trained for one year at a velocity half way between their LT velocity and their maximal running velocity. Significant increases in VO_2 and running velocity were observed for the trained groups at the LT, FBLCs, and peak, with the >LT group exhibiting greater improvements. Despite the changes in workload and cardiorespiratory demand at given La concentrations, there were no significant alterations in RPE. The authors concluded that RPE remains stable at the LT, FBLCs, and at peak workloads, independent of fitness level or training intensity. A close examination of the results suggests that RPE responses reported as stable pre- to post-training for the exercise groups actually represented some change in RPE. The LT training group showed increases in RPE at FBLCs above the LT (*d* = 0.59 to 1.00, 22% to 34%). Similarly, nonsignificant changes in RPE from pre- to post-training for the >LT training group also represented increases in perceptions of strain at the LT (*d* = 0.51, 20 %) and FBLCs (*d* = 0.26 to 0.61, 10% to 23%). The conclusion that RPE remains stable at particular La concentrations independent of state of training appears dubious and is not supported by effect size calculations. Rather, changes in RPE may have reflected some alteration in absolute and relative VO_2 and absolute exercise intensities that increased from pre- to post-training. These considerations were previously discussed in the section on VO_2 as a mediator of RPE.

In contrast to the conclusions of the previous authors, but more consistent with the magnitude of change calculations reported above, Held and Marti (1999) suggested that variations in fitness level may disturb the relationship between RPE and La. Examining the results from an incremental treadmill test of 319 male and 145 female members of Swiss national teams, Held and Marti compared the running performance and RPE responses of the 10% worst and 10% best endurance trained participants at 4.0 $mmol.l^{-1}$ FBLC. At running velocities associated with 4.0 $mmol.l^{-1}$ FBLC, RPE responses from the fittest group were significantly greater than the less fit group for men (*d* = 3.0) and women (*d* = 2.4). Running velocities associated with 4.0 $mmol.l^{-1}$ FBLC were also significantly greater for the fittest compared to the least fit participants (males, *d* = 10.0; females, *d* = 9.0). Similar to the results of Haskvitz et al. (1992), fitter participants were able to sustain greater workloads relative to perceptions of exertion, but the contention that RPE remains stable at FBLCs is not supported by these results. Further analysis by Marti and Held indicated that RPE was closely associated with actual running velocity rather than the

La concentration at these velocities. A major limitation in this study is the potentially wide range of sports from which the participants were recruited. The huge effect sizes reported for the differences in running velocity at 4.0 $mmol.l^{-1}$ FBLC suggest that the bottom 10% of endurance trained athletes were probably not endurance trained at all and were possibly not accustomed to treadmill testing. No information was supplied about the sports from which the two groups were chosen. One might expect that the top 10% of endurance trained athletes would be habitually accustomed to ergometer exercise testing. The bottom 10%, however, were more likely to come from sports in which endurance performance was less important and were less likely to be accustomed to treadmill exercise testing. Borg (1982) suggested that mode of exercise affects RPE relationships, and Boutcher et al. (1989) demonstrated that the effect of training on RPE relationships is perturbed when testing is conducted using ergometers that do not match individuals' mode of training. Other results presented earlier suggest that some aspects associated with treadmill running might provide input into the effort sense (Ceci & Hassmén, 1991).

DeMello et al. (1987) compared RPE and ventilatory responses at exercise intensities relative to both La accumulation (LT) and cardiorespiratory demand (percentages of VO_2max) in trained ($n = 20$) and untrained ($n = 20$) men and women. Groups were tested using a GXT with ten three-minute stages separated by three-minute rest periods. Results indicated that, despite the LT occurring at a significantly greater percentage of VO_2max for trained compared to untrained participants ($d = 1.6$), there was no significant or meaningful difference in RPE at the LT between the two groups. When responses were compared at various percentages of VO_2max, results showed that La, $V_E.VO_2^{-1}$, and RPE were lower for trained compared to untrained participants. Close associations were also reported for RPE with La ($r = .67$ to .84) and $V_E.VO_2^{-1}$ ($r = .61$ to .77) suggesting that RPE may be more closely associated with La levels and ventilatory variables associated with metabolic acidosis than with percentage of VO_2max. The authors concluded that the LT is an important metabolic marker for perceptions of exertion during exercise.

Boutcher et al. (1989) compared the effect of 10 weeks of differentiated training ($n = 5$, run training; $n = 6$, cycle training; $n = 5$, controls) on RPE and VO_2 at the LT. Both treadmill and cycle ergometer exercise tests were performed pre- and post-training. The results from the training-specific ergometer tests indicated that, despite significant increases in VO_2 at the LT for the trained groups from pre- to post-training (runners, 59% change; cyclists, 39% change), RPEs for trained participants were lower at the LT (runners, 26% change; cyclists, 15% change). The researchers reported different results between training specific and non-specific exercise tests. Increases in VO_2 at the LT were markedly larger for training-specific ergometer tests. Perceptual responses showed small increases in RPE (runners, 13% change; cyclists, 7% change) from pre- to post-training at the LT for non-specific ergometer tests, compared to moderate decreases in RPE for training-specific ergometer tests. Combined, these results suggest that improvements in exercise efficiency on training-specific protocols may influence both physiological and perceptual responses to exercise. In general, these results suggest that increases in workload at the LT following training do not result in increases in perceptions of exertion. Moreover, although the authors concluded that RPE at the LT was not affected by training, the reductions in RPE reported above suggested that training attenuates perception of exertion at the LT. These results also suggest that VO_2 is unlikely to be a primary mediator of exertion. Reductions in RPE, combined with marked increases in respiratory demand, indicated that VO_2 was not an important mediator of RPE at exercise intensities associated with the LT.

Simon, Young, Gutin, Blood, and Case (1983) investigated the RPE responses of highly trained (*n* = 6) and sedentary untrained (*n* = 6) participants at the AT and at 4.0 mmol.l^{-1} FBLC. The testing protocol involved an incremental bicycle ergometer test with increases in workload of 30 W every two minutes. Results showed that trained participants rated their exertion significantly higher at the AT than untrained participants (*M* = 13.5 and 10.5, respectively). The authors, however, did not report at what percentage of VO_2max participants' AT occurred. There was a 4.9% mean difference in percentage of VO_2max at which 4.0 mmol.l^{-1} FBLC occurred between trained (85.0% of VO_2max) and untrained (80.1% of VO_2max) participants. Accompanying RPEs were reported as similar for trained (*M* = 16.2) and untrained participants (*M* = 15.4), but represented the same mean difference (4.9%) as percentage differences in VO_2max. The authors also reported a strong correlation between percentage of VO_2max and RPE (*r* = .94) and concluded that RPE was more closely related to percentage of VO_2max than percentage of the AT. The suggestion that RPE may be more closely tied to exercise workloads relative to percentage of VO_2max than La accumulation appears to contradict the findings of other researchers. Some questions exist, however, regarding the incremental exercise protocols and the estimation of La accumulation used in this study. The authors did not report the method used to determine the AT, and the two-minute workloads used during testing were unlikely to elicit steady-state La concentrations. Exercise durations shorter than five minutes may overestimate the AT exercise intensity (Bourdon, 1999) and, thus, the two-minute workloads in this study may have distorted the results.

Researchers examining RPE relationships at exercise intensities relative to cardiorespiratory demand most often compare responses at workloads relative to percentage of VO_2max or the ventilatory threshold. Hill et al. (1987) examined the effect of training on RPE at the ventilatory threshold. University students were assigned to either a training (n = 17) or a control group (n = 10). The training group engaged in interval training on a cycle ergometer (3 days per week) and running or cycling continuous exercise (2 days per week) for seven weeks. The control group performed "usual activities" that did not include vigorous exercise. RPE, HR, work rate, and percentage of VO_2max were compared at the ventilatory threshold using ANCOVAs with pre-test scores used as covariates. The training group exhibited lower HRs and RPEs at an absolute workload of 100 W, and a greater VO_2max compared to the control group. At the ventilatory threshold, however, post-intervention RPEs were similar between groups, despite the ventilatory threshold occurring at a significantly higher percentage of VO_2max (d = 1.3), workload (d = 1.4), and HR (d = .58) for the trained participants. The authors concluded that the ventilatory threshold might be an important anchor for RPE and that training appears to reduce RPE at a given percentage of VO_2max. A limitation of this study is the use of one-minute intervals during the GXT to calculate the ventilatory threshold. It is questionable whether participants would have achieved steady-state ventilatory responses in one minute. Short workload durations during incremental exercise tests risk underestimating the ventilatory threshold.

Travlos and Marisi (1996) investigated RPE and physiological responses of high fit (n =10) and low fit (n =10) participants during continuous incremental exercise on a cycle ergometer. Participants performed 10-minute workloads at 40%, 50%, 60%, 70%, and 80% of VO_2max with HRs and RPEs recorded every five minutes. Analyses revealed a significant main effect of group membership for RPE, but not for HR. RPEs were lower for the high fit, compared to the low fit group at all workloads. Consistent with the findings of Hill et al. (1987), Travlos and Marisi concluded that at the same relative workload, high fit individuals perceive themselves to be under less strain than less fit individuals. The authors, however, did not describe the testing protocols for the determination of VO_2max. The authors described high and low fit participants as individuals with a VO_2max above 56 ml.kg.min^{-1} and below 46 ml.kg.min^{-1} respectively. There was no mention of participants being excluded from this study. This selection procedure suggests that, of the twenty participants recruited, none were found to have a VO_2max between 46 and 56 ml.kg.min^{-1}. This gap indicates that participants were screened prior to recruitment, although the authors did not report such a procedure. The lack of procedural and analytical detail provided by the authors casts some doubt over the results presented.

Spodaryk et al. (1990) examined the relationship between La and RPE in 22 well-trained female distance runners and 10 untrained women at various percentages of VO_2max. All participants performed an incremental VO_2max test on a cycle ergometer and power outputs were calculated that corresponded with 25%, 50%, 75%, and 90% of each participant's VO_2max. On a separate day, participants performed three-minute bouts of cycling at each of the four workloads. RPE (CR-10) and La were recorded at the end of each stage. Results showed little change in RPE and La responses at lower power outputs between trained and untrained women. At 75% and 90% of VO_2max, trained women reported significantly lower RPEs compared to untrained women, despite increased La concentrations for the trained group. Three-minute work intervals, however, may have been insufficient for La concentrations to reach steady-state. The finding of differences in RPE between trained and untrained participants at high, but not low, workloads appears consistent with the findings of other researchers who have proposed that important cardio-metabolic mediators influence perceptions of exertion at higher, but not lower, exercise intensities (Noble et al., 1986; Robertson et al., 1986).

Ekblom and Goldbarg (1971) examined RPE relationships before and after eight weeks of aerobic training ($N = 8$). RPE, HR, La, and ventilatory parameters were determined at 25%, 50%, 75%, and 100% of participants' pre- and post-training VO_2max. In contrast with some of research presented earlier (e.g., Hill et al., 1987), but consistent with the findings of Simon et al. (1983), RPEs were reported as the same across all workloads adjusted for VO_2max. Submaximal HRs were lower following training, but were reported as the same at a given percentage of VO_2max. RPEs were also the same at a given La concentration pre- to post-training. Spodaryk et al. (1990) reported that lower RPEs at relative oxygen uptakes for trained compared with untrained women were not evident until participants were working at 75% of their VO_2max. Differences in RPE pre- to post-training may have occurred had Ekblom and Goldbarg tested at a higher submaximal workload (e.g., 90%). No control group comparisons and inadequate power to detect differences in RPE also limit the findings of this research.

Skrinar et al. (1983) examined the effect of six to eight weeks of endurance training on RPE, La, and neurotransmitter production in 15 women. Participants completed a submaximal treadmill test of three 20-minute stages completed at 60%, 70%, and 80% of VO_2max before, during (approximately midway), and after training. Local, central, and overall RPE were recorded every five minutes and blood samples were taken at the completion of each stage for the determination of La, adrenaline, and noradrenaline. Mean RPE responses across all exercise intensities were calculated at each testing session. The authors reported significant reductions in central and overall RPE, but found no differences in local RPE from pre- to post-training. Although La and stress hormones did not differ between trials, significant correlations were reported between La and local RPE ($\eta = .68$), and between adrenaline and noradrenaline and central RPE ($\eta = .54$ and $\eta = .63$, respectively). Although the finding that overall RPE was reduced at the same relative oxygen demand is consistent with other research, this result is limited without control group comparisons.

Docktor and Sharkey (1971) investigated RPE responses relative to HRs. They investigated the effects of five weeks of training on RPE and physiological responses of five healthy, non-athletic college men. Responses during GXTs with one-minute intervals were compared from pre- to post-training The authors reported that workloads required to reach a HR of 150 bpm increased significantly pre- to post-training, but RPE at a HR of 150 bpm remained virtually unchanged despite the increased workload. This study, however, involved some methodological issues that undermine the reliability of these results. Using a HR of 150 bpm to compare workloads and RPEs may not elicit sufficient physiological demand for anaerobic acidosis to contribute to perceptions of exertion. La and V_E have been identified as major contributors to RPE (Noble & Robertson, 1996), but are unlikely to mediate perceptions of exertion at such low exercise intensities. It is possible that, had testing in this study occurred at maximum or near maximum exercise intensities, important perceptual cues would increase RPE responses concomitantly with workload both before and after training. The low intensity at which training was conducted (incrementally graded treadmill walking at 3.5 mph until HR reached 180 bpm three times per week) and the relatively short duration of the training program makes the omission of higher workloads during testing a serious flaw. The results are further limited by the lack of control group comparisons. Also, the authors used the 21-point RPE scale (Borg, 1962), which has not demonstrated a strong linear relationship with workload during incremental exercise.

Snyder et al. (1993) investigated the effect of two weeks of moderate training, overtraining, and recovery training on seven well-trained male cyclists. Participants completed a GXT to exhaustion at the beginning and end of the moderate and overtraining periods and at the end of the recovery training period. Starting at 150 W, workloads were increased 50 W every five minutes and RPE and La were measured during the last 30 seconds of each stage. The authors found that following a period of overtraining, athletes exhibited decreases in La concentrations at a given RPE. RPEs remained stable across training periods, but La concentration decreased during overtraining. The authors concluded that such reductions in La without concomitant reductions in RPE were indicative of overtraining. Although these results appear to contradict earlier findings, this study differs in that training consisted of intensities designed to elicit exhaustive, overtraining outcomes rather than intensities designed to overload participants to improve fitness.

Garcin, Fleury, and Billat (2002) conducted a similar investigation that investigated the effect of eight weeks of high intensity (overreaching) training on the relationship between RPE and La in high-level middle-distance runners ($N = 8$). The participants performed incremental exhaustive exercise tests on an indoor running track before and after eight weeks of overreaching training (5 sessions per week). Following training participants demonstrated lower La concentrations at running velocities associated with the VO_2max and velocities half way between the VO_2max and the LT. Slightly higher La concentrations were observed at the LT. In contrast to the results reported by Snyder et al. (1993), participants demonstrated higher RPEs at each test point following training. Consistent with Snyder et al., participants exhibited decreases in La concentrations at given RPEs following a period of overtraining. The authors concluded that declines in the ratio between La and RPE were indicative of short-term overtraining.

Martin and Andersen (2000) examined the relationship between RPE and HR during training and taper with 11 collegiate and elite level cyclists. Participants completed six weeks of high intensity interval training followed by one week of taper (66% reduction in weekly training time) and completed GXTs at baseline, each week of training, and following taper. GXTs involved a discontinuous protocol with four-minute work stages separated by one-minute recovery periods. Beginning at 110 W, workloads were increased 40 W every stage until voluntary withdrawal. Results indicated large increases in power output from baseline to week-six and week-six to taper. Power-HR and power-RPE regression slopes were lower following training. No difference was reported in the HR-RPE regression slope, but there were significant increases in RPE at a HR of 150 bpm from baseline to week-six and from week-six to taper. Further, the magnitude of decrease in HR for a given RPE during training was a strong predictor of an athlete's performance after taper. The authors noted that athletes who reported higher RPEs for a given HR were becoming more and more fatigued during high intensity training. This fatigue represented a training overload, but resulted in these athletes responding well to taper with improved performances. These results, in combination with Garcin et al. (2002) and Snyder et al. (1993), suggest that overtraining can result in decreases in indices of physiological demand (i.e., La and HR) and stable or increased RPE responses. In other words, athletes might feel more fatigued, and unable to attain the same level of physiological activation following overtraining.

Researchers have investigated the perceptual and physiological responses of elite athletes during on- and off-season exercise testing. Martin et al. (1999) examined the relationship between power output, HR, La, pH, bicarbonate, and RPE before and after two months of endurance training with six members of a national cycling team. Testing involved a GXT beginning at 100 W with 50 W increases every five minutes and a 30TT where participants cycled at the highest power output possible for 30 minutes. Tests were performed pre- and post-training with dependent measures recorded every five minutes. RPE responses were only taken during the 30TT. Due to the small sample size and the risk of making a Type II error, the authors interpreted results in terms of effect sizes. GXT results followed expected physiological adaptations to training with large increases pre- to post-training in peak power output (d = .95) and power at the AT (D_{max}; d = .95), and a large decrease in La at D_{max} (d = .92). The 30TT data showed large increases pre- to post-training in power output (d = 2.11) and La (d = .92), and large decreases in pH (d = 1.07) and bicarbonate (d = 1.22). Only a small decrease in HR (d = .29) and a small increase in RPE (d = .28) were observed. Despite much greater workloads and large increases in indicators of local muscular strain, perceptions of exertion were only slightly greater. Moreover, the La-RPE relationship was altered. For example, before training an RPE of 19 was associated with a La of 10 and after training this RPE was associated with a La of 12. This result suggests that high intensity training allow athletes to tolerate greater exercise demands without concomitant increases in perceptions of exertion.

Although much of the research presented on the effect of training on RPE relationships is equivocal, methodological problems and differences may be, in part, responsible for disparate outcomes. For example, some researchers reported that reductions in La and HR at absolute exercise intensities for trained participants were not matched by reductions in RPE. Some of these studies, however, may not have used sufficient physiological demand during exercise testing for perceptual signals associated with metabolic acidosis to distinguish between the RPE responses of trained and untrained participants (e.g., Docktor & Sharkey, 1971; Morgan, 1977; Patton et al., 1977). Researchers that employed high exercise testing workloads found that training reduced physiological demand at absolute exercise testing with subsequent reductions in RPE (Hassmén, 1990; Morgan & Pollock, 1977).

Comparisons of RPE responses at exercise intensities relative to La accumulation suggest that RPE remains stable at the LT and FBLCs between trained and untrained participants, despite untrained individuals working at greater exercise workloads. Comparing RPE responses at exercise intensities relative to ventilatory thresholds and maximum oxygen consumption demonstrates that RPE decreases in trained participants irrespective of greater exercise workloads. Taken together, these research findings demonstrate that efficiencies in exercise metabolism achieved as a result of training are matched by a reduction in perceptions of physical strain at absolute exercise workloads. Research examining the effect of training on RPE relationships also demonstrates that RPE is more closely associated with La concentrations than cardiorespiratory demand.

RPE and Temperature

Most research findings have shown that higher environmental temperatures result in greater physiological activation that does not elicit concomitant increases in RPE. Research results have suggested that increased ambient temperatures increase HRs at all stages of exercise and increase La concentrations at higher exercise intensities (Dimri, Malhorta, Sen Gupta, Kumar, & Aora, 1980; Leweke, Brück, & Olschewski, 1995; Nadel, 1983). Researchers have reported no increases in RPE (Glass et al., 1994; Pandolf et al., 1972) or increases of lesser magnitudes when compared to HR (Bergh et al., 1986; Maw et al., 1993) and La responses (Smith, Petruzello, Kramer, & Misner, 1997). These findings suggest that the HR-RPE and La-RPE relationships are altered by heat stress in that similar perceptual responses are associated with higher HRs and higher La concentrations. Further, these results indicate that individuals may not sense the increased physiological exertion of exercising in higher environmental temperatures.

It is possible that temperature regulatory responses might mediate RPE either through changes in recognised physiological cues, such as V_E, or through alterations in sweating and skin temperature. Ambient temperatures affect skin temperature although research findings are equivocal regarding a link between skin temperature and RPE. Noble et al. (1983) demonstrated that skin temperature accounted for more variance in RPE in hot compared to moderate conditions. Despite reporting a strong correlation between skin temperature and thermal sensation ($r = .71$), Kamon et al. (1974) were not able to demonstrate a meaningful relationship between skin temperature and RPE ($r = -.33$). Similarly, Glass et al. (1994) and Pandolf et al. (1972) reported significant changes in skin temperature with ambient temperature without reporting any associated changes in RPE.

Other physiological indices of thermal strain, such as sweating and blood flow, may mediate perceptions of exertion. This mediating role, however, may be dependent upon the degree to which individuals perceive sweat and skin redness as uncomfortable (Noble & Robertson, 1996). It is unlikely that core body temperature directly mediates RPE in higher ambient temperatures, and it has long been established that core temperature is proportional to metabolic rate and independent of environmental temperatures (Armstrong & Pandolf, 1988). Core body temperature, however, may play some role in RPE responses because other thermoregulatory responses (e.g., sweat rate, blood flow) rely on a threshold increase in core body temperature (Sawka & Wenger, 1988).

Bergh (1986) reviewed unpublished data that compared cardiorespiratory, La, and RPE responses during graded exercise in 15°C and 45°C conditions. Results showed that increases in RPE during exercise in elevated temperatures were associated with larger increases in HR so that, for a given RPE, HRs were greater in high ambient temperatures. Although Bergh reported that the La-RPE relationship remained unchanged across temperature conditions, close inspection of the results suggests that, at higher exercise intensities, La levels appear higher in relation to RPE in the hot condition. This result is consistent with the findings of Glass et al. (1994) and suggests that the La-RPE relationship may change in different environmental temperatures at high, but not low exercise intensities.

Glass et al. (1994) compared cardiovascular and perceptual responses during steady-state exercise in a variety of environmental temperatures. Participants ($N = 6$)

performed 30 minutes of exercise on a cycle ergometer at 80% of VO_2max in low (14.7°C), moderate (21.0°C), and high (27.4°C) temperatures. HR, blood pressure, La, skin temperature, VO_2, V_E, and RPE were measured at 10, 20, and 30-minute time points. As expected, HR was significantly elevated in the high temperature condition compared to the moderate and low temperature conditions. At minute-30, La and respiratory effort were significantly greater in the high temperature condition compared to the low temperature condition. RPEs, however, varied very little (1% to 5%) between each condition across time and were consistent with VO_2. The authors concluded that RPE is more closely associated with metabolic intensity as measured by VO_2, and that participants did not sense the extra cardiovascular strain during exercise in moderate and high temperatures.

Bergh et al. (1986) examined La, HR, and RPE responses of six untrained men during submaximal GXTs in high (45°C) and low (15°C) environmental temperatures. RPE and HR were significantly elevated during exercise in high temperatures, but heat stress altered the relationship between HR and RPE, so that RPE was lower at a given HR during the 45°C condition compared to the 15°C. The authors reported significantly higher La levels during the 45°C test, but only at the two highest workloads. The La-RPE relationship was unchanged across conditions. Glass et al. (1994) and Bergh (1986) also reported large heat induced increases in La at higher workloads and reported a change in the La-RPE relationship. Peak La responses reported by Bergh et al. ($M = 5.0$ mmol.l^{-1}) were much lower than that reported by Glass et al. (8.0 mmol.l^{-1}), suggesting the possibility that the workloads presented in this study were too low to demonstrate sufficient increases in La and alter the La-RPE relationship.

Investigating the relationship between HR and RPE, Pandolf et al. (1972) reported cardiorespiratory and RPE responses of 10 fit males during different steady-state exercise test protocols under neutral (24°C), hot (44°C), and extreme (54°C) conditions. Consistent with the findings of Glass et al. (1994), the authors reported that, despite significant increases in HR as environmental temperatures increased, there were no associated increases in RPE. HR was more strongly correlated with thermal sensation ($r = .64$) and discomfort ($r = .59$) than with RPE ($r = .48$), whereas RPE was most closely correlated with V_E ($r = .77$). The authors concluded that RPE does not seem to be a function of any individual physiological parameter, such as HR, and that heat does not appear to alter RPE responses. Changes in the HR-RPE relationship reported in this study are consistent with other research findings.

Maw et al. (1993) investigated the effect of hot (40°C), neutral (24°C), and cool (8°C) conditions on perceptual, thermoregulatory, and HR responses of 14 males during steady-state exercise tests. Participants performed steady-state exercise for 30 minutes at workloads equivalent to an RPE of 13 (determined during pre-testing in the neutral condition). HR increased significantly in the hot condition compared to the neutral and cool conditions throughout exercise, and differences tended to increase as exercise time continued. In the hot condition, RPE was higher compared to the cool condition throughout exercise, and higher than the neutral condition by the completion of the exercise test. The relationship between HR and RPE was altered, so that for a given RPE, HR was 10-14 bpm greater in the hot condition. The authors concluded that hot environmental conditions provide an additional stimulus to HR above that provided by exercise, and that this additional heat-induced cardiac stimulus is not perceptually salient.

Smith et al. (1997) investigated the effect of neutral (13.7°C) and extreme (89.6°C) environmental temperatures on RPE and physiological responses of firefighters ($N = 16$) during simulated work exercises. Measures were taken during, upon completion, and 10 minutes following a 16-minute firefighting activity. Increases were observed in HR and La during the firefighting activity and after ten minutes of recovery. At minute-sixteen, HR was 37 bpm higher and La increased 68% in the hot condition compared to the neutral condition. RPE was approximately 15% higher in the hot condition, but relative increases in HR and La exceeded increases in RPE. There was a moderate relationship between HR and RPE in the neutral condition (r = .57 to .48), but little association in the hot condition (r = .01 to .18). Because the relative increases in physiological parameters exceeded increases in RPE in the hot condition the authors concluded that participants were perceptually underestimating the physical demand of the task in the hot condition.

Kamon et al. (1974) compared RPE and physiological responses from 10 participants during submaximal steady-state exercise performed in 24°C, 44°C, and 54°C conditions. Responses were compared between trials performed in 24°C temperatures at intensities between 40% and 70% of VO_2max, and trials performed in 44°C and 54°C temperatures at 40% of VO_2max. RPE was recorded every two and a half minutes and HR, ventilatory variables, and skin and rectal temperatures were recorded every five minutes throughout exercise. Comparisons of results at the same relative workloads revealed no significant difference in RPE and VO_2 between conditions, however, significant increases in HR were detected as environmental temperatures increased. A strong correlation was reported between RPE and V_E (r = .77), but not RPE and HR (r = .48). It is questionable, however, whether the exercise demands were sufficient for important mediators of perceived exertion to influence RPE responses. This result is consistent with Glass et al. (1994) who also reported that RPE responses across different environmental temperatures were more closely associated with respiratory variables. Although the results of this research are consistent with other findings, there are methodological issues that potentially limit these results. The criterion for selection of participants was a VO_2max in excess of 51 $ml.kg.min^{-1}$ to ensure that each participant could complete 30 minutes of ergometer work at the required intensities. This selection criterion limits the generalisation of these findings to relatively fit people in the population. Also, because HRs did not exceed 160 bpm during any of the trials, the exercise demands presented may not have been sufficient for important mediators of perceived exertion to influence RPE responses.

Not all research findings support the contention that acute variations in ambient temperatures affect RPE relationships during exercise. Potteiger and Weber (1994) examined HR, La, and RPE responses of nine trained cyclists during steady-state exercise on a cycle ergometer at 30°C, 22°C, and 14°C. In each condition, cyclists exercised to exhaustion at an intensity corresponding to their onset of blood lactate accumulation (4.0 $mmol.l^{-1}$; as determined from an earlier GXT). RPE, La, and HR were determined every five minutes throughout exercise and compared at minute-five, minute-10, midpoint, and at exhaustion. The authors reported no significant differences in time to exhaustion, HR, La, or RPE between the three exercise conditions. The authors concluded that HR, RPE, and La were not affected by changing environmental temperatures. The authors suggested that the range of temperatures used might not have been sufficient to demonstrate changes in these variables. The range of temperatures used, however, were greater than those used by Glass et al. (1994), who demonstrated significant differences in HR between conditions. A more likely explanation may be the low statistical power and the somewhat conservative alpha level (.01). An examination of HR and RPE responses suggests that HR tended to increase as environmental temperatures increased, but RPE responses demonstrated no meaningful or consistent differences between conditions. Despite some researchers' conclusions to the contrary, these results are supportive of many previously reported findings.

Galloway and Maughan (1997) compared the physiological and perceptual responses of eight healthy males during steady-state exercise (70% of VO_2max) to exhaustion in cold (3.6°C and 10.5°C), moderate (20.6°C), and hot (30.5°C) environmental temperatures. Exercise metabolites and respiratory function were measured every 15 minutes, skin and rectal temperatures and HR recorded every 5 minutes, and RPE determined every 10 minutes throughout the exercise tests. Time to exhaustion was significantly affected by temperature, with the shortest duration observed in the 30.5°C condition (*M* = 51.6 minutes) and the longest in the 10.5°C condition (*M* = 93.5 minutes). HRs were significantly higher during exercise at 30.5°C compared to all other conditions from minute-35 to exhaustion. La concentrations were not different between trials at rest or during exercise. Overall RPE was significantly higher during the 30.5°C condition compared to all other conditions at 20, 30 and 40-minute time points. These results contradict the findings presented earlier, and suggest that elevations in thermal stress during exercise affect RPE. Other researchers have reported little effect of ambient temperature on rectal temperature (e.g., Kamon et al., 1974; Maw et al., 1993; Pandolf et al., 1972), whereas Galloway and Maughan reported significant increases in rectal temperature as ambient temperature increased. Changes in rectal temperature during short-term exercise are believed to be independent of ambient temperatures, but more dependent upon the relative intensity of exercise (Armstrong & Pandolf, 1988). Other researchers have used exercise durations around 30 minutes at intensities around 40% of VO_2max, whereas Galloway and Maughan tested participants at 70% of VO_2max to exhaustion. Greater workloads and exercise durations in this study may, therefore, have influenced perceptual responses by increasing thermal sensations at higher temperatures.

Skinner, Hustler, Bergsteinova, and Buskirk (1973) compared exercise responses of eight obese and eight lean young men at 24°C and 34°C conditions. The participants performed GXTs to self-imposed maximum on a bicycle ergometer and a treadmill in both conditions. Workloads were increased every two minutes with V_E, VO_2, and HR recorded at the completion of each workload. In contrast with other findings, the relationship between HR and RPE remained constant for both temperature conditions, for both groups, and between each testing protocol. This contradictary result may be because a GXT was used, lasting 15-20 minutes, rather than the typically employed steady-state protocol, which usually lasts a minimum of 30 minutes. Shorter exercise durations may result in greater local thermal sensations (Mihevic, 1981), whereas, high-intensity, continuous exercise may draw more from central indicators of strain. Because local factors are believed to contribute more to overall RPE than central factors (Robertson, 1982), the shorter duration of exercise in this study may have resulted in an elevated RPE that tracks more closely increases in HR.

Research results have suggested that acute exposure to exercise performed in hot compared to moderate temperature conditions results in elevations in HR that are not accompanied by equivalent increases in RPE. Moreover, results have indicated that RPE responses to exercise under different environmental temperatures are more closely related to respiratory variables, such as V_E. These findings are not surprising given that HR is unlikely to be a physiological parameter that is consciously monitored during exercise (Mihevic, 1981; Robertson, 1982; Noble & Robertson, 1996), and research has demonstrated that respiratory variables are important mediators of perceptions of exertion (Cafarelli & Noble, 1976; Robertson et al., 1986). Research findings presented in a previous section also support a role for ventilatory variables as primary mediators of RPE regardless of environmental temperature (e.g., Noble et al., 1973; Glass et al., 1994). The La-RPE relationship appears to be altered at higher, but not lower exercise intensities. Although some research results have suggested that RPE increases with higher ambient temperatures, these changes may be mediated by the relative fitness of individuals. When higher RPEs were reported during exercise in hot compared to moderate temperature environments, researchers used participants who were less physically active (Pandolf, 2001). Research results presented in this section that demonstrated no increases in RPE in higher environmental temperatures used relatively fit participants (Glass et al., 1994; Kamon et al., 1974; Pandolf et al., 1972).

RPE and Altitude

The effect of altitude on exercise performance has been widely researched. Exercise performance is reduced during acute exposure to high altitude concurrent with reductions in VO_2max (Welch, 1987). An approximate reduction of 3% occurs in VO_2max for every 300 m of altitude above 1500 m (Armstrong, 2000). The reduction in maximal oxygen consumption is associated with an impairment of gas exchange mechanisms caused by a lower pressure gradient between alveolar and pulmonary capillaries. This impairment in oxygen transport limits the delivery of oxygen to working muscles resulting in increases in V_E to narrow the alveolar-capillary pressure gradient (Fulco & Cymerman, 1988). Cardiac output is also greater during acute altitude exposure, due primarily to increases in HR (Hahn & Gore, 2001). La concentrations during exercise at absolute workloads are increased at altitude (Sutton, 1977). When exercise intensities are adjusted to account for reductions in VO_2max, however, La, HR, and V_E remain similar between sea level and altitude testing (Bouisou, Peronnet, Brisson, Helie, & Ledoux, 1986; Escourrou, Johnson, & Rowell, 1984; Knuttgen & Sltin, 1973; Young et al., 1982).

The limited numbers of published studies investigating the effect of altitude exposure on RPE have produced inconsistent results. Comparisons between research findings are difficult because researchers have employed varying experimental designs and exercise conditions. It appears that RPE responses at absolute exercise intensities will increase during acute altitude exposure (Robinson & Haymes, 1990). When exercise intensities are adjusted to account for reductions in maximal exercise capacity at altitude, however, researchers have demonstrated reductions in RPE compared to sea-level responses at the same percentage of VO_2max (Horstman, Weiskopf, & Robinson, 1979; Young et al., 1982).

Young et al. (1982) explored the effect of acute and chronic high altitude exposure on RPE relationships in low altitude residents. Participants ($N = 8$) performed 30 minutes of steady-state exercise (85% of VO_2max) at sea level and following acute (less than two hours) and chronic (18 days) exposure to altitude (4,300 m). Exercise intensities during steady-state tests conducted at altitude were adjusted to account for reductions in VO_2max. Ventilatory variables, HR, and differentiated RPE were compared between the three exercise conditions. Results showed that maximal V_E increased slightly and VO_2max and submaximal VO_2 decreased significantly after acute and chronic high altitude exposure compared to sea level. These changes to ventilatory parameters resulted in significant and large increases in respiratory effort, suggesting increased respiratory effort when exercising at altitude. HR was also significantly lower during the acute and chronic high altitude conditions compared to sea level. Nonsignificant and negligible differences were reported in La between sea level and acute altitude tests, but significant and large reductions in La were observed after chronic altitude exposure. Despite the apparent increase in respiratory effort during acute altitude exposure, overall and central RPEs demonstrated nonsignificant reductions at altitude. Chronic altitude exposure resulted in significant reductions in local RPE concomitant with the large decrease in La in this condition. These results support the suggestion that local factors dominate RPE responses. Despite an increase in central RPE following chronic altitude exposure, overall RPE was reduced compared to sea level because of large reductions in La and local perceptions of strain. Such results raise concerns about relating overall RPE responses with physiological parameters that more closely reflect differentiated exercise demands. Overall, the results of this study suggest that increases in central indicators of physiological demand are not associated with equivalent changes in RPE. The changes in central physiological activation detected at altitude, however, occurred in parameters identified as unlikely to be consciously monitored during exercise (e.g., HR, VO_2; Mihevic, 1981; Robertson, 1982).

Maresh et al. (1993) examined RPE and physiological responses of eight moderate altitude natives (2,200 m) and six low altitude natives (366 m) during continuous incremental exercise at their resident altitude and following two days of hypobaric hypoxia equivalent to an altitude of 4,270 m. Exercise tests followed a continuous incremental protocol with increases of 50 W every two minutes until exhaustion. Cardiorespiratory variables, La, and RPE were compared at workloads equivalent to 35%, 55%, 75%, and 85% of condition-specific VO_2max. Results revealed that in the hypoxic condition, VO_2max declined 15% in the moderate altitude group and 34% in the low altitude group. Hypobaric hypoxia resulted in significant reductions in submaximal VO_2 responses for both groups at all intensities above 35% of VO_2max. No significant differences in V_E were detected for either group between resident and hypobaric hypoxia testing. Significant reductions in La in the hypoxic condition were reported for both groups at 55% and 85% of VO_2max, but not at maximum workload. The moderate altitude group also exhibited a significant decrease in La at 75% of VO_2max. Both groups exhibited significant reductions in HR in the hypoxic condition at 75% of VO_2max, but HRs were lower at maximum workloads in the low altitude group only. During resident altitude testing, both moderate altitude and low altitude groups demonstrated similar differentiated RPE responses. In the hypoxic condition, however, central RPE responses from the moderate altitude group were significantly less than the low altitude group at 75% and 85% of VO_2max. This alteration in central perceptions of effort also contributed to significantly lower overall RPEs for the moderate altitude group at 75% of VO_2max. Although not explicitly reported or commented on, graphical representations suggested that the moderate altitude group exhibited consistent reductions in overall RPE during exercise in hypobaric hypoxia compared to resident testing. The low altitude group demonstrated no such alterations in perceptual responses. These differences in RPE responses may reflect an acclimatisation to altitude conditions in the moderate altitude group. Hypobaric hypoxia did not alter VCO_2 and elicited smaller changes in VO_2max in the moderate altitude group. This result might indicate a more efficient gas exchange metabolism in this group resulting in lower RPE responses. Despite an apparent alleviation of central perceptions of exertion, V_E was not significantly altered in either group between exercise conditions. Unfortunately means and standard deviations for V_E were not reported and effect sizes could not be calculated.

Horstman et al. (1979) reported RPE and cardiorespiratory responses from 20 participants during short-term and prolonged steady-state exercise at sea level and at altitude (4,300 m). During short-term exercise, participants cycled for six minutes at workloads equivalent to 60%, 80%, and 95% of altitude specific VO_2max. HR and RPE were determined during the last ten seconds of each workload and respiratory variables calculated over the last minute. Prolonged exercise involved cycling at 85% of VO_2max (altitude specific) to exhaustion. HR and RPE were compared every five minutes of exercise, and respiratory variables were calculated during the seventh minute of exercise. During short-term exercise, VO_2 was consistently lower (approximately 20%) at high altitude compared to sea level, whereas V_E was consistently higher (approximately 12%). There were negligible differences in HR. RPE responses were significantly lower at altitude at lesser exercise intensities, but converged as workloads increased so there was little difference above 80% of VO_2max. Prolonged exercise elicited no meaningful differences in HR. During the seventh minute, V_E was significantly greater (23%) at altitude than at sea level. Similar to the results obtained from short-term exercise, RPE was significantly lower at altitude during the early part of prolonged exercise, but by 75% of endurance time there was little difference. The authors concluded that local factors dominated the perception of effort at intensities that did not stress V_E and circulation. Further, RPE was reduced at altitude in concert with the muscle mechanics involved with reduced exercise workloads. At higher exercise intensities, increases in ventilatory responses during exercise at altitude increase RPE responses relative to sea level tests. The relationship between respiratory variables and RPE presented in this study do not meet expected outcomes. Young et al. (1982), however, also demonstrated large increases in respiratory effort without alterations in RPE during exercise at altitude.

Maresh et al. (1988) investigated short-term (10 to 21 days; $n = 52$) and long-term (greater than two years; $n = 55$) residents at altitude during GXTs to voluntary exhaustion at moderate altitude (2,200 m). RPE, cardiorespiratory, and La responses were compared at maximal workload and at 60% of altitude-specific VO_2max. No significant differences between groups were reported on any of the measured variables at maximal workloads aside from short-term resident female participants who had significantly greater V_E. At 60% of VO_2max, however, short-term residents had significantly elevated V_E and RPE compared to long-term residents. All other variables were not significantly different, except respiratory effort that was significantly elevated in short-term resident females. The authors concluded that lower perceptions of effort by long-term residents at sub-maximal levels might be explained by lower V_E. These results conflict with the findings of Young et al. (1982) by showing alterations in V_E following acute altitude exposure and demonstrating concomitant changes in perceptions of physiological strain. Such a result provides further support for V_E as a primary mediator of RPE and upholds the contention of some authors that V_E is consciously monitored during exercise (Pandolf, 1983; Robertson, 1982). It is difficult, however, to make direct comparisons between the results of Young et al. and Maresh et al. because of differences in experimental design between the two studies. Young et al. used a within groups design to test participants after an exposure of less than 2 hours to high altitude, whereas Maresh et al. compared short and long-term residents at moderate altitude.

Robinson and Haymes (1990) examined cardiorespiratory, metabolic, and RPE responses from seven healthy male participants during 90 minutes of rest followed by 30 minutes of steady-state exercise in four experimental conditions. Participants were exposed to normoxic and hypoxic (12% O_2) conditions in moderate (25°C) and cold (8°C) temperatures. Steady-state cycle intensities equated to 50% of HR reserve and were not adjusted to account for reductions in exercise capacity in the hypoxic conditions. HR, V_E, respiratory exchange ratio, and VO_2 were determined every 15 minutes throughout rest and exercise and La was recorded after 45 and 90 minutes of rest and five minutes post-exercise (peak La). RPE was determined at minute-15 and minute-30 of exercise. HRs were significantly elevated (independent of temperature) in the hypoxic condition compared to the normoxic condition throughout rest and during exercise. Hypoxia did not significantly affect V_E during rest, but elicited significant elevations during exercise. VO_2 and respiratory exchange ratio were significantly lower in the hypoxic conditions during rest and throughout exercise. Post-exercise La was significantly higher and nonsignificant increases in La were reported at minute-45 and minute-90 in the hypoxic compared to the normoxic condition. Average RPE responses across minute-15 and minute-30 were significantly greater in hypoxia compared to normoxia. Given the hypoxia induced increases in primary mediators of perceptions of exertion (e.g., V_E, La), it is not surprising that RPE responses were higher during exercise in hypoxia. It is difficult, however, to make comparisons between these results and other studies in this section because Robinson and Haymes did not adjust exercise intensities in hypoxia to account for diminished exercise capacities in this condition. In this study participants were working at a higher percentage of their maximal capacity in the hypoxic condition. A major limitation of this study is the measurement of physiological and perceptual responses at different time points. It is difficult to gain meaningful information about RPE relationships when RPEs are only reported at relatively small exercise durations and averaged across two time points that are inconsistent with the measurement points of the physiological responses.

Hahn et al. (2001) investigated the effect of acute altitude exposure on RPE and physiological responses in elite level athletes. Cross-country skiers ($N = 9$) performed discontinuous incremental ski-striding protocols in simulated sea level and 1,800 m altitude conditions. Comparisons made at workloads corresponding to percentages of sea level VO_2max showed increases in La concentrations above 80% of VO_2max and increases in V_E and RPE above 70% of VO_2max. A significant difference in HR was detected at 70% of VO_2max, but HR responses between conditions converged as workloads approached maximum. Time to exhaustion was also significantly reduced at altitude. Although increases in V_E have been shown in some studies that reported comparisons at altitude-adjusted workloads (Horstman et al., 1979; Young et al., 1982), the finding of increased V_E, La, and RPE is not consistent with most research findings that used adjusted workloads. Increases in V_E, La, and RPE at absolute workloads are consistent with previous research findings (Robinson & Haymes, 1990). These results confirm that, when workloads are not adjusted for altitude-induced reductions in VO_2max, the higher relative workloads involved in exercise performed at altitude result in greater physiological and perceptual responses.

Brosnan, Martin, Hahn, Gore, and Hawley (2000) examined perceptual and physiological responses of road cyclists ($N = 8$) during exercise tests performed at simulated sea level and 2,100 m altitude conditions. In each condition, athletes performed a series of three maximal 10-minute cycling bouts (five minutes of active rest between each set) and six maximal 15-second cycling sprints (three minutes of active rest between each set). The altitude condition reduced power outputs during both protocols compared to sea level. For the 10-minute work bouts, HR and RPE responses were similar between conditions, but meaningful increases in La were detected upon completion of each interval from sea level (7.9, 8.1, and 8.4 $mmol.l^{-1}$) to altitude conditions (8.9, 9.6, 10.9 $mmol.l^{-1}$). During cycling sprints, HR and RPE responses were also similar between conditions, whereas La was greater during the first sprint set, but similar following successive sprints. The authors suggested that, because equivalent HRs were found in both conditions during both protocols, athletes were working at similar relative exercise intensities. The finding of similar HR and RPE responses at sea level and altitude when workloads were adjusted is consistent with previous findings. Different La responses reported during the 10-minute work bouts compared to the sprint protocols suggest that the La response to altitude might be mediated by exercise duration. The nonsignificant increases in La at altitude, however, did not translate to changes in RPE.

The small number of studies investigating RPE relationships during exercise performed at altitude and the variations in experimental methodologies used in these studies make it difficult to compare research findings. Results suggest that comparisons between exercise performed at absolute workloads at sea level and at altitude result in increases in RPE at altitude concomitant with greater relative exercise intensities (Robinson & Haymes, 1990; Hahn et al., 2001). When exercise intensities are adjusted to account for reductions in VO_2max, some researchers have reported reduced RPE responses at the same relative exercise intensity (Horstman et al., 1979; Young et al., 1982). These results suggest that RPE follows absolute workloads rather than respiratory responses at altitude. Maresh et al. (1988), however, demonstrated increases in RPE at the same relative exercise intensity at altitude with accompanying increases in V_E.

RPE During Upper and Lower Body Exercise

At a given submaximal power output, upper body exercise produces greater physiological strain than lower body work. Most research findings have demonstrated greater submaximal La, V_E, VO_2, VCO_2, and HR during arm crank compared to cycle exercise (Sawka et al., 1982; Taguchi & Horvath, 1987; Vokac, Bell, Bautz-Holter, & Rodahl, 1975). Arm crank exercise, however, results in lower maximal power outputs than cycle exercise (Sawka et al., 1982; Vokac et al., 1975) and lower maximal VO_2, V_E, La, and HRs (Bergh, Kanstrup, & Ekblom, 1976; Franklin et al., 1983; Kang, Chaloupka, Mastrangelo, & Angelucci, 1999). Researchers have reported similar physiological responses between arm crank and cycle exercise when adjustments are made in submaximal workloads to account for ergometer specific exercise capacity (Pimental, Sawka, Billings, & Trad, 1984; Sawka et al., 1982). Reductions in maximal exercise capacity for upper body compared to lower body exercise have been attributed to smaller muscle mass, reduced potential to generate muscular tension, reduced oxidative capacity, and reduced blood perfusion to skeletal muscle. For a comprehensive review of the differences in the physiological responses between arm and leg exercise see Sawka (1986). Differences in physiological responses between upper and lower body exercise result in alterations to perceptual responses during submaximal arm and leg exercise. At given absolute workloads, higher RPEs have been observed during submaximal arm exercise compared to leg exercise (Eston & Brodie, 1986; Pandolf et al., 1984; Pivarnik et al., 1988). Researchers comparing upper and lower body exercise at workloads adjusted for modality specific exercise capacity have reported similar physiological and perceptual responses (Hetzler et al., 1991; Pandolf et al., 1984).

Sargeant and Davies (1973) examined the relationship between RPE, HR, and respiratory variables for six healthy males performing one-arm, two-arm, one-leg, and two-leg exercises on a modified cycle ergometer. Trials consisted of 30 minutes of incremental exercise (six minutes for each of five progressive workloads) for each exercise mode with workloads adjusted for protocol specific exercise capacity. Reflecting differences in the maximal power outputs and the size of muscle masses involved, results showed that HR, VO_2, and V_E were higher during leg exercises than arm exercises at maximal exertion. Most of these differences were removed, however, when responses were standardised for differences in VO_2max between arm and leg exercises. Regression calculations showed a close relationship between RPE and percentage of VO_2max across exercise modalities. Regression analyses also indicated that, for a given RPE, power output, HR, VO_2, and V_E increased with increases in the muscle mass employed (one arm, two arm, one leg, and two leg). Although limitations exist in this study (i.e., small sample size, no measurement of peripheral mediators of RPE, no reporting of mean submaximal perceptual and physiological comparisons), the results suggest that maximal exercise capacity and the size of the muscle mass involved in exercise affects both physiological and perceptual responses to exercise.

Eston and Brodie (1986) reported results from 19 participants performing graded arm and leg work on a modified cycle ergometer. Each participant performed four minutes of arm and leg exercise at absolute workloads of 49, 73.5, and 98 W. VO_2, V_E, respiratory exchange ratio, and HR were recorded continuously and RPE was determined in the last 15 seconds of each workload. At given absolute submaximal workloads, arm exercises produced greater RPE, VO_2, V_E, respiratory exchange ratio, and HR compared to leg exercises with differences in physiological parameters increasing in magnitude as workloads increased. The magnitude of difference in steady-state RPE responses between arm and leg exercise across the three workloads (44% to 38%) most closely reflected differences in V_E (21% to 40%) and exceeded differences in other central indicators of physical strain (HR, 8% to 28%; VO_2, 9% to 26%). Greater RPE responses during upper body exercise are likely due to increases in V_E, but might also be attributable to local mediators of RPE. Researchers have suggested that local factors are more likely to limit exercise capacity during arm compared to leg exercises (Sawka et al., 1982). Although peripheral contributors to fatigue were not measured in this study, large increases in V_E during upper body exercise might reflect alterations in La and pH. The researchers also reported stronger correlations between RPE and VO_2 and HR for arm (HR $r = .87$; VO_2 $r = .78$) compared to leg exercise (HR $r = .62$; VO_2 $r = .65$). Lower correlations for leg exercises are likely due to lower relative workloads and decreased input from central and local mediators of exertion. The researchers did not calculate correlations with RPE and V_E, which is the most likely of the measured variables to mediate perceptions of exertion.

In research described in an earlier section on RPE and HR, Gamberale (1972) explored the relationship between RPE, HR, VO_2, and La during a variety of physical activities. Male university students ($N = 12$) performed graded cycle ergometer work, weight lifting from shoulder height to a shelf 25 cm higher, and bouts of pushing weights in a wheelbarrow on a 100 metre course. Although the different activities do not allow for direct comparisons between perceptual and physiological responses at standardised power outputs, there were notable differences in RPE relationships between the different activities. Alterations in RPE relationships appeared to reflect the relative amount of muscle mass recruited to fulfil performance demands. For a given HR, RPE was incrementally higher for activities recruiting smaller muscle masses compared to larger muscle masses. Gamberale also reported that activities that produced high La in relation to VO_2 (i.e., lifting weights), also produced greater RPEs in relation to HR. Given that activities employing smaller muscle masses deliver lower maximal exercise capacities, it is not surprising that weight lifting elicited greater La concentrations at absolute levels of

VO_2. Greater La concentrations and lower HRs for a given RPE during the upper body task supports the contention that local factors might play a more important role in determining RPE during upper body tasks. Gamberale did not calculate maximal exercise capacities for the different tasks, making it impossible to compare responses at the same relative workloads. The small range of intensities obtained during the weight lifting and wheelbarrow tasks also limits the results from this study.

In research presented in an earlier section on RPE and VO_2, Pandolf et al. (1984) reported RPE and physiological responses from nine healthy young males during steady-state arm crank and cycle ergometer exercise. With at least three days separating each of four steady-state exercise tests, participants performed arm crank and cycle ergometer work for 60 minutes at power outputs corresponding to a VO_2 of 1.6 $l.min^{-1}$ and 60% of ergometer specific VO_2max. Differentiated RPEs, cardiorespiratory variables, and blood pressure were recorded every ten minutes and La determined every 20 minutes of exercise. Local, central, and overall RPEs were significantly lower for cycle compared to arm exercises at all time points during absolute workload tests. RPEs during the relative workload tests were not significantly different during arm and leg exercises. In contrast with tests performed at absolute workloads, RPEs were consistently higher for cycle compared to arm exercise. Mean physiological responses during steady-state tests were not reported, so direct comparisons of RPE relationships between upper and lower body exercise at comparable time points were not possible. Results from regression analyses indicated that La accounted for the most variance in RPE across both exercise modalities. respiratory effort made large contributions to cycle work, whereas diastolic and systolic blood pressures were key contributors to RPE for arm exercises. The association between RPE and blood pressure indices might be expected given that blood pressure (Miles, Sawka, Glaser, & Petrofsky, 1983) and total peripheral resistance (Stenberg, Åstrand, Ekblom, Royce, & Saltin, 1967) have been shown to be higher for activities involving smaller muscle masses. Greater blood pressure responses have also been reported during upper body activities, possibly due to isometric muscle contractions involved in torso and upper body stabilisation, particularly at higher exercise intensities (Toner, Sawka, Levine, & Pandolf, 1983). Some authors have suggested that haemodynamic parameters, such as blood pressure, might provide central signals to the perception of effort (Robertson, 1982), and the results from Pandolf et al. have indicated that this parameter may be particularly important in mediating RPE during upper body exercise. The atheoretical criteria for the order of inclusion of predictor variables into the regression analyses (stepwise), however, raise questions about these results because of the likely multicolinearity between selected independent variables. Also, it is difficult to ascertain the amount of unique variance each physiological parameter contributed to RPE during arm and leg exercises. Further, it is inappropriate to run a regression with nine participants and 11 independent variables. Stepwise regression analyses require a 40 to 1 participant to variable ratio (Tabachnick & Fidell, 1996).

Pivarnik et al. (1988) examined thermoregulatory, physiological, and perceptual responses during upper and lower body exercise performed in different environmental temperatures. Participants ($N = 8$) performed 60 minutes of single-limb steady-state exercise at the same absolute workload (75W) on arm and leg ergometers in 23°C and 33°C conditions. VO_2, HR, skin and rectal temperatures, and RPE were compared. Comparisons between arm and leg work within the same temperature conditions revealed that the absolute workload represented 60% of arm VO_2max and 37% of leg VO_2max. In concert with these differences in relative exercise intensity, HR and RPE were significantly greater during arm compared to leg exercises. The authors concluded that RPE appears closely related to relative workloads regardless of exercise mode. The findings from this study are limited, however, by the relatively low workload administered that resulted in a maximum HR of 140 bpm during arm exercise. Such a low workload might also have contributed to the finding of no significant or meaningful differences in VO_2 between arm (1.56 and 1.59 $l.min.kg^{-1}$) and leg (1.56 and 1.59 $l.min.kg^{-1}$) exercise. Other researchers have demonstrated differences in VO_2 between arm and leg exercises only at higher, but not lower workloads (Sawka et al., 1982; Vokac et al., 1975).

Borg et al. (1987) explored the relationship between perceptions of exertion, HR, and La with eight participants during graded arm and leg ergometer work. Four minute workloads of 40, 70, 100, 150, and 200W for leg and 20, 35, 50, 75, and 100W for arm exercise were presented to participants and perceived exertion (RPE and CR-20), HR, and La were determined during the last 30 seconds of each workload. All perceptual and physiological responses were greater for arm compared to leg exercise at comparable absolute workloads. For a given RPE and CR-20 response, HRs were lower during arm compared to leg work, whereas La concentrations were consistently higher at comparable perceptual ratings for arm work. These results are consistent with the findings of Gamberale (1972) and suggest that factors associated with local muscular fatigue might be more important mediators of RPE than central indicators of physiological strain. The findings of high La concentrations relative to RPEs during arm work might be expected because participants exceeded their AT between the second and third workloads (70 to 100W) for arm exercise, but not until the final workload for the leg exercise (200W). Because of a lower AT during arm work (Davis, Vodak, Wilmore, Vodak, & Kurtz, 1976; Reybrouck, Heigenhauser, & Faulkner, 1975), La would provide more input to the perception of effort during arm compared to leg exercises.

Greater RPEs at the same absolute power outputs during upper body compared to lower body exercise can be attributed to lower maximal power outputs for upper body work, but also to other aspects of upper body physiology. Upper body work produces lower ATs (Davis et al., 1976) and includes isometric muscle contractions involved with torso stabilisation (particularly at higher exercise intensities) that can increase physiological activation and increase arterial blood pressures (Clausen, 1976; Sawka et al., 1982). Some evidence also suggests that upper body musculature contains a greater proportion of fast-twitch fibres (Johnson, Polgar, Weightman, & Appleton, 1973; Sucheela & Walton, 1969) and that upper body activity results in the earlier recruitment of fast-twitch motor units (Cerretelli, Pendergast, Paganelli, & Rennie, 1979; Sawka et al., 1982). Compared to slow-twitch fibres, fast twitch fibres have a lower contractile coupling efficiency and, therefore, have greater energy costs (Sawka, Petrofsky, & Phillips, 1981; Wendt & Gibbs, 1973). Another consideration that is of particular interest for this thesis is that differences in maximal performance between upper and lower body exercise might vary according to the state of training of individuals. Upper body trained athletes have produced VO_2max responses during arm ergometer exercise that are close to 90% of their cycle ergometer VO_2max (Cerretelli et al. 1979; Seals & Mullin, 1982; Vrijens, Hoekstra, Bouckaert, & Van Uytvanck, 1975). Studies with untrained participants have reported arm VO_2max responses that are, on average, 70% of their cycle ergometer maximum (Sawka, 1986).

Characteristics of the relationship between RPE and physiological variables for upper and lower body exercise have not been extensively investigated. The few studies conducted to date reveal some similarities in results, but are also limited by inconsistencies in experimental design and exercise protocols employed. Theoretical expectations and most experimental evidence suggest that RPE responses are greater during upper body exercise at absolute intensities, but that perceptual responses are similar when compared at workloads adjusted for protocol specific exercise capacities. The studies presented in this section suggest that factors associated with local muscular fatigue, such as La, pH, and muscle blood flow, might be more important in mediating RPE during upper body work. It is difficult, however, to make definitive conclusions about RPE relationships during upper compared to lower body exercise. The research is characterised by small sample sizes, small ranges of exercise intensities, comparisons made at absolute power outputs, few results reported concerning submaximal perceptual and physiological comparisons at the same relative exercise demand, and only two studies measuring peripheral mediators of RPE.

Statistical and Research Design Concerns

Methodological limitations hamper much of the existing research on the relationship between RPE and physiological parameters. Of particular concern are the small numbers of participants used in research and the subsequent issues of low statistical power, possible Type II errors, the unjustifiable equating of "no significant difference" with "no meaningful difference," and the nonexistence of power analyses (especially with nonsignificant results). Clarifying meaningful differences in RPE research has received little attention and is not resolved by employing indicators of statistical significance. For example, what may be important or meaningful from a clinical or performance perspective may not always be statistically significant, and this issue is particularly relevant in studies using small sample sizes. A related issue is researchers who do not supply sufficient information (e.g., means and standard deviations) for others to calculate effect sizes (although this can be partly attributed to the publication policy of some exercise physiology journals). In some cases, authors have presented information for significant differences only (e.g., Hahn et al., 2001), when a full reporting of results would best serve the reader by supplying detailed descriptive information for nonsignificant results. The interpretation of meaningful differences is especially important when examining RPE relationships in elite athletes, where small effects can have important consequences on performance outcomes. A number of researchers have recommended the reporting of effect sizes for interpreting the magnitude and meaning in outcome measures (e.g., Andersen & Stoové, 1998; Kazis, Anderson, & Meenan, 1989). Although the abandonment of the use of statistical significance in interpreting research results is not advocated, it is perhaps best to consider estimates of significance, combined with indicators of effect size as the necessary statistical tools for judging the meaning of results.

The problem of small sample sizes and low statistical power is exacerbated when researchers dichotomise (e.g., Noble at al., 1983) or trichotomise (e.g., Ljunggren et al., 1987) samples according to scores on a continuous variable. When already small sample sizes are split into smaller subgroups, a subsequent loss of data and statistical power occurs. In addition, splitting a continuous variable to construct participant groups leads to a questionable separation of individuals that is not based on any meaningful difference. For example, Ljunggren et al. (1987) trichotomised their sample according to La accumulation at minute-15 of exercise to see if the groups differed on RPE responses and percentage of ST muscle fibres. Groups were categorised as having elevated, intermediate, or low rates of La accumulation. This arbitrary distinction could conceivably mean that someone with a La accumulation of 4.4 might be categorised in the intermediate group, whereas another participant with a La accumulation of 4.5 might be categorised in the elevated group. Cohen (1983) noted that when continuous variables are split in this way, squared correlations with other variables are typically reduced by about 36%.

Serious questions arise regarding the reliability of results from multiple regression analyses when small sample sizes are used to estimate the relationship between RPE and physiological parameters. Stepwise regressions have been performed where the number of independent variables actually exceed the number of participants in the study (e.g., Noble et al., 1973; Pandolf et al., 1984). It is recommended that stepwise regressions have a minimum participant to variable ratio of 40 to 1 (Tabachnick & Fidell, 1996). The extremely low participant to variable ratios used in RPE research give rise to the risk of overfitting the data, making any subsequent generalisation of results questionable. Another basic assumption of regression analyses that is violated in RPE research is the requirement for variables entered into regressions to be relatively independent. Given the integration of physiological systems in providing input to the effort sense, there is likely to be a high degree of multicolinearity among physiological covariates of RPE. In addition, the assumption of independence for variables entered into regressions is violated with repeated-measures experimental designs.

Another research design issue of concern in the RPE literature is using two different experimental conditions to examine RPE relationships. When examining the relationship between variables using statistics such as correlations or regressions, a fundamental assumption is that all observations of variable X are independent. By combining results from two experimental conditions to calculate correlations between variables (e.g., Löllgen et al., 1977; Löllgen et al., 1980), similar factors may affect the participants in one condition, but not participants in the other. When two conditions are used in research, separate associations should be calculated so that the condition effects are constant and do not influence the estimation of the relationship. When overall associations are calculated across different conditions, the observations are not independent and the final estimated relationship is a compromise between the relationships specific to the two conditions.

A methodological and statistical issue of particular concern for this research is how the *relationship* between RPE and physiological variables is investigated across experimental conditions. The typical procedure to investigate RPE relationships has involved the measurement of RPE and selected physiological variables at a given workload or physiological demand. Differences between groups or conditions are then determined for each of the variables and conclusions are based on comparing these changes separately. For example, training resulted in an increase in heart rate at the LT, but no change in RPE. Authors often do not go on to analyse the changes in variables in relation to each other. Particularly for research that describes differences as significant or not, this method potentially obfuscates meaningful changes in RPE relationships. To overcome this problem, researchers might consider the use of ratios between RPE and physiological variables to examine more precisely how perceptual and physiological responses to exercise change in relation to each other across conditions. This method might be particularly useful in circumstances where small changes potentially have important consequences in applied settings (e.g., elite athletic performance). This method has been recently used to investigate HR-RPE responses to taper in elite cyclists (Martin & Andersen, 2000) and La-RPE responses to overreaching in competitive cyclists (Snyder et al., 1993) and high-level middle-distance runners (Garcin et al., 2002).

Another issue related to this thesis is the choice of workloads at which to compare RPE relationships between conditions. Because the RPE literature suggests that RPE relationships are influenced by workload, this thesis will compare perceptual and physiological responses at low workloads, the AT, and at maximal workloads. Most studies that have compared RPE responses relative to La accumulation have used the LT to compare responses. The AT was used in this thesis because, for highly trained athletes, the LT was considered to represent too low an intensity for La accumulation to have a meaningful input into perceptions of exertion. Because highly trained athletes are able to maintain relatively high steady-state La concentrations (above the LT), the point at which workloads cause a rapid increase in La (AT) was considered a more relevant point at which to compare RPE responses.

This Thesis

This thesis examined the relationship of RPE with HR and La in elite athletes across a variety of conditions. The first study investigated RPE relationships in elite swimmers during in-season and off-season training to examine the effect of state of training on the relationship between RPE and selected physiological variables. It was hypothesised that athletes would attain higher HRs and La concentrations for a given RPE during in-season compared to off-season exercise tests. The second study examined RPE relationships in elite road-cyclists during exercise in moderate and hot environmental conditions. It was hypothesised that the high temperature condition would produce greater HRs at all workloads and higher La concentrations at high workloads for a given RPE compared to the moderate temperature condition. The third study compared RPE relationships in elite cross-country skiers in simulated sea-level and altitude conditions. It was hypothesised that La and HR responses would be similar at a given RPE during altitude and sea-level tests. The fourth study investigated the relationship between RPE and selected variables in elite road-cyclists and elite kayakers to compare RPE relationships during upper and lower body exercise. It was hypothesised that upper body exercise would produce greater HR and La responses for a given RPE compared to lower body exercise.

In light of the statistical and research design issues highlighted in the previous section, the data in this thesis were analysed and interpreted primarily in terms of effect size. The overall effect of experimental conditions across workloads will be interpreted using eta squared (η^2) and these results will be decomposed into multiple one degree of freedom effects (Cohen's *d*) at individual workloads.

CHAPTER 3

A COMPARISON OF HEART RATE-RPE AND LACTATE-RPE RELATIONSHIPS IN ELITE SWIMMERS DURING IN-SEASON AND OFF-SEASON TRAINING

Method

Participants

Members of the Australian National Swimming Team participated in this study (males = 8, females = 4). The swimmers were between 20 and 27 years old and specialised in freestyle, individual medley, butterfly, breaststroke, and backstroke. The swimmers competed in events over distances from 50 to 1500 metres.

Measurement

Rating of Perceived Exertion scale (RPE). Perceived exertion was determined upon completion of each swim stage using the 15-point RPE scale (Borg, 1985) anchored by 6 (*no exertion at all*) and 20 (*maximal exertion*). A complete description of the Borg scale and its psychometric properties is found in Chapter 2 (p. 11 - 18). All athletes in the study had been exposed to the RPE scale on several occasions during previous exercise tests and were familiar with rating their perceived exertion using this scale.

Heart rate (HR). HR (beats per minute) was measured throughout each swim using a Polar Sports Tester HR monitor. The Polar Sports Tester HR monitor recorded minute-HR during exercise based on continuous sequences of three heartbeats.

Lactate (La). Capillary blood samples were taken every five minutes in 100uL gas blood collection capillary tubes (Corning). Samples were drawn from this tube (25uL) and placed in an epindorf tube with a 50uL solution of cell lysing agent (YSI 1515) and buffer concentrate (YSI 2357) and analysed for La using a YSI 2300 glucose and La analyser.

Procedure

Each participant performed an incremental aerobic test (7 x 200 m swim) six months apart during in-season (IS) and off-season (OS) training periods. Swimmers undertook the series of seven 200-metre swims in their specialist strokes. Each swim was incrementally graded from easy to maximal and undertaken on a 5-minute cycle. Target times for each swimmer were calculated before the test and then discussed with the swimmer, the coach, and the testing staff. Times were calculated based on the swimmer's 200-metre personal best. Emphasis was placed on even splits and target times were given before each swim. The time for each 100 metres was recorded. Immediately upon completion of each swim stage, HR was recorded and participants were shown the RPE scale and asked verbally to rate their overall exertion. Following each swim stage the participants exited the pool and a blood sample was taken from the earlobe using the capillary puncture method. The swimmer then had a short break (depending on the time taken to extract the blood sample), commencing the next swim exactly five minutes after starting the preceding swim. This cycle was continued until seven swims were completed.

Data Analysis

The variables of swimming velocity, HR, and La during IS and OS tests were plotted against RPE over the seven stages of each incremental swim test. To examine further the relationship between RPE, HR, and La, ratios between HR and RPE and La and RPE were compared between IS and OS tests. HR-RPE and La-RPE ratios were calculated for each participant at low intensity (minute-five), the AT (using modified D-max calculation), and high intensity (minute-35) during the incremental swim tests. Within groups 2 (season) x 3 (time) ANOVAs were used to assess differences between IS and OS tests for RPE ratios at minute-five, the AT, and at minute-35 of the incremental swim tests. All assumptions associated with the univariate ANOVA with repeated-measures were tested and degrees of freedom adjusted according to the Huynh-Feldt method when the assumption of sphericity was violated. Interactions and main effects for workload and training time are reported in terms of significance tests ($p < .05$). Traditional effect size calculations for analyses of variance come in the form of eta squared (η^2), the amount of variance in a variable accounted for by group membership, or in this case, time of testing (e.g., being tested during IS and OS training). The American Psychological Association (APA) have stated in their Publication Manual (APA, 2001) that, "... multiple degree-of-freedom effect indicators tend to be less useful than effect indicators that decompose multiple degree-of-freedom tests into meaningful one degree-of-freedom effects - particularly when these are the results that inform the discussion" (p. 26). In this study, it is more meaningful to determine the magnitude of difference in RPE ratios between tests at different workloads. Effect sizes are, therefore, reported in the form of η^2 for main effects and interactions, and Cohen's *d* for differences between IS and OS training at low intensity, the AT, and high intensity. Effect size calculations are particularly important given the small sample size used in this study (Tabachnick & Fidell, 1996). In the behavioural sciences, an η^2 of .01 and a Cohen's *d* of .20 represent small effects; an η^2 of .06 and a Cohen's *d* of .50 represent medium effects, and an η^2 of .14 and a Cohen's *d* of .80 represent large effects (Cohen, 1988).

AT was calculated according to the modified D-max method. Using this method, the AT was defined as the point on the La-Power curve that is the maximal distance away from a straight line drawn between the LT (the workload preceding a 4.0 $mmol.l^{-1}$ rise in La above resting levels) and the final workload (Cheng et al., 1992). RPE, HR, and La responses at the AT were calculated using software (ADAPT, 1995) that rapidly and systematically determines the AT using the calculations described above.

Results

Table 3.1 presents means and standard deviations for RPE, HR, and La responses at minute-five, the AT, and minute-35 for IS and OS graded swimming tests. *Figure 3.1* illustrates the relationship between RPE and HR across all stages of the incremental swim tests performed during IS and OS training. These results show that athletes exhibited higher HRs and, at most workloads, displayed slightly lower RPE responses during tests performed in IS compared to OS training. *Figure 3.2* shows the relationship between RPE and La across all stages of the incremental swim tests performed during IS and OS training. At the lowest exercise intensity, RPE and La responses were similar between conditions. As workloads approached the AT, La responses were slightly higher, but RPE responses were slightly lower during IS compared to OS tests. As workloads increased beyond the AT, La responses were greater during IS training whereas RPE responses were similar. *Figure 3.3* shows the relationship between RPE and swimming velocity across all stages of the incremental swim tests performed during IS and OS training. Greater swimming velocities were obtained throughout IS compared to OS tests, but RPE responses were similar or slightly lower during the IS tests.

Table 3.1

Means and Standard Deviations for RPE, HR, and La for IS and OS Incremental Exercise Tests.

Minute	RPE				HR				La			
	In-Season		Off-Season		In-Season		Off-Season		In-Season		Off-Season	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
5	7.75	1.66	7.50	1.00	138.58	11.12	133.58	8.79	1.61	0.38	1.73	0.48
AT	16.17	1.95	16.67	1.30	182.42	5.78	176.83	7.32	4.15	0.79	3.95	0.48
35	18.67	1.07	18.75	1.22	189.75	6.61	186.50	8.72	11.04	2.79	9.68	2.13

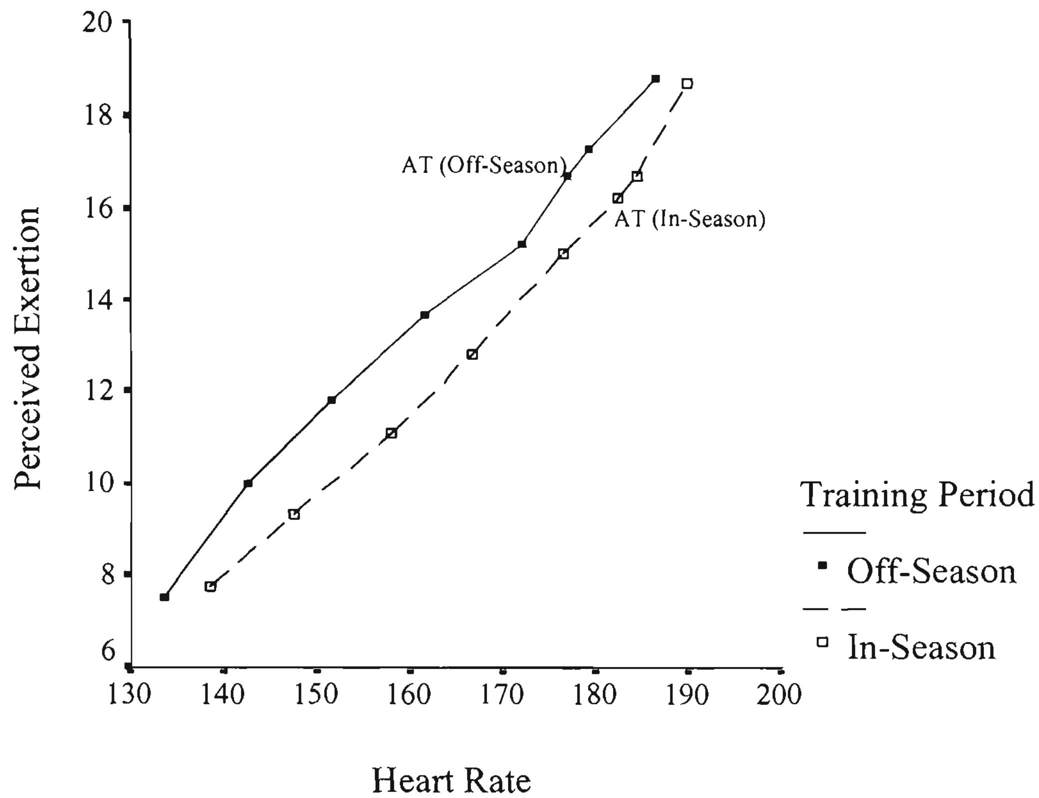

Figure 3.1. Variation in RPE with HR during IS and OS incremental exercise tests.

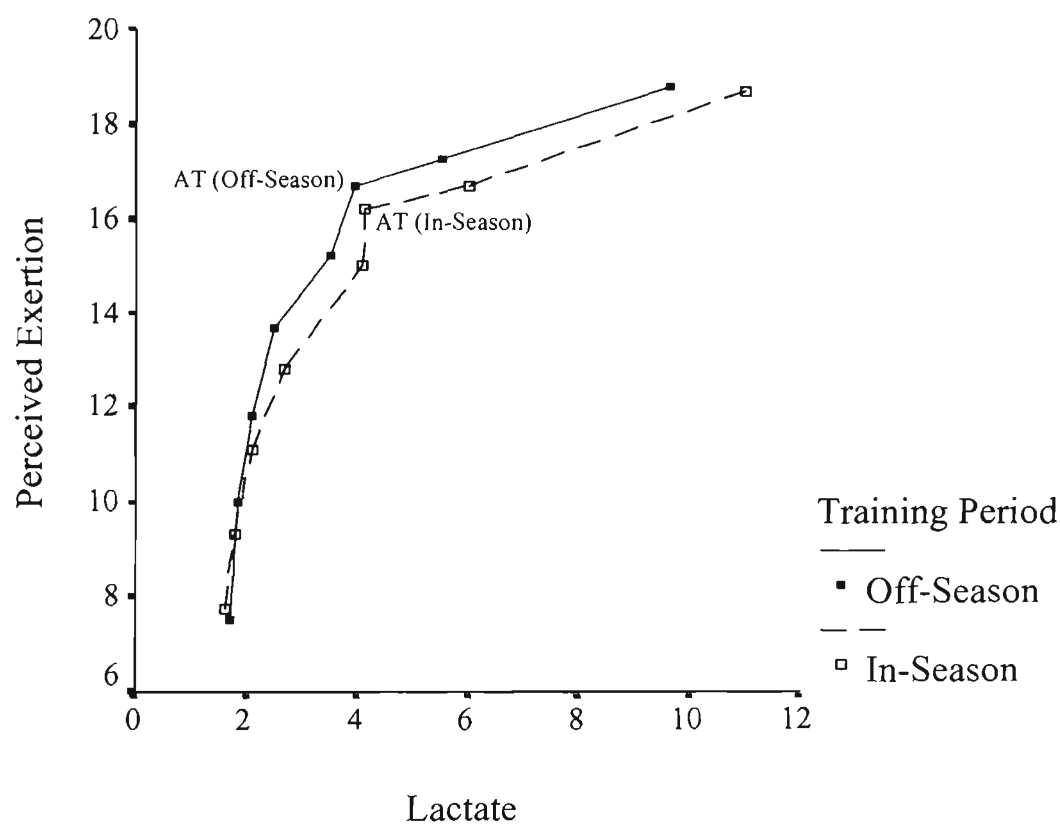

Figure 3.2. Variation in RPE with La during IS and OS incremental exercise tests.

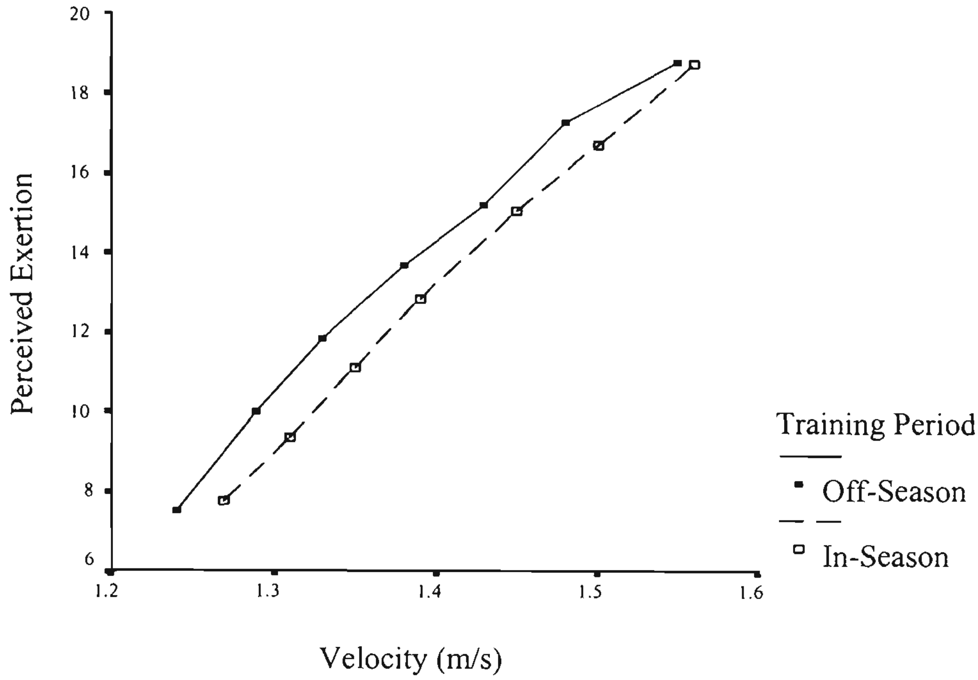

Figure 3.3. Variation in RPE with swimming velocity during IS and OS incremental exercise tests.

Ratios between HR and RPE, and La and RPE were calculated at minute-five, the AT, and minute-35 for each participant in order to determine differences in RPE relationships between IS and OS training at different workloads. Table 3.2 presents the means and standard deviations for HR-RPE and La-RPE ratios at minute-five, the AT, and minute-35 for IS and OS incremental swimming tests. Table 3.3 shows the results of the within-groups ANOVAs for IS and OS HR-RPE and La-RPE ratios at the three workloads.

Table 3.2

Means and Standard Deviations for HR-RPE and La-RPE Ratios for IS and OS Incremental Exercise Tests.

Minute	HR-RPE				La-RPE			
	In-Season		Off-Season		In-Season		Off-Season	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
5	18.51	3.51	18.12	2.89	0.22	0.06	0.23	0.06
AT	11.43	1.34	10.68	1.07	0.26	0.06	0.24	0.04
35	10.21	0.85	10.00	1.02	0.59	0.15	0.52	0.12

Table 3.3

F-values, df, Significance Levels, and Effect Sizes Comparing RPE Ratios Between IS and OS Incremental Exercise Tests Across Three Exercise Workloads.

Source	HR-RPE					La-RPE				
	F-value	*df*	*p*	η^2	Power	*F*-value	*df*	*p*	η^2	Power
IS/OS Training	0.80	1.00	> .05	.07	.13	2.88	1.00	> .05	.21	.34
Workload	138.53	1.11	< .05	.93	1.00	93.66	1.12	< .05	.90	1.00
Interaction	0.21	1.12	> .05	.02	.36	1.77	1.27	> .05	.14	.17

There was a significant main effect of workload on the HR-RPE relationship, with decreased HRs for a given RPE with increases in workload. The extremely large effect of workload ($\eta^2 = .93$) was mostly due to the large reduction in HR-RPE between minute-five and the AT (as indicated in Table 3.2). Results showed a medium effect of training ($\eta^2 = .07$) and a small interaction effect of training and workload ($\eta^2 = .02$) on the HR-RPE relationship, although the small sample size contributes to a lack of statistical significance. An examination of the magnitude of differences in the HR-RPE relationship between IS and OS training at different workloads showed only a slight difference at minute-five ($d = 0.09$), a medium to large difference at the AT ($d = 0.62$), and a small to medium difference at the highest intensity ($d = 0.35$). These results represented a 23 percentile point shift in HR relative to RPE at the AT and a 14 percentile point shift in HR relative to RPE at minute-35.

There was a significant main effect of workload on the La-RPE relationship. This result represented an extremely large effect ($\eta^2 = .90$), with increased La for a given RPE with increases in workload (as indicated in Table 3.2). Results showed a large effect of training ($\eta^2 = .21$) and a large interaction effect of training and workload ($\eta^2 = .14$) on the La-RPE relationship. An examination of the magnitude of differences in the La-RPE relationship between IS and OS training at different workloads showed little difference at minute-five ($d = 0.13$), a small to medium difference at the AT ($d = 0.34$), and a medium difference at the highest intensity ($d = 0.52$). These results represented a 13 percentile point shift in La relative to RPE at the AT and a 20 percentile point shift in La relative to RPE at minute-35.

Discussion

The results from this study suggest that the relationships between RPE and HR and RPE and La change across different training periods for elite swimmers. Athletes exhibited higher HRs, La concentrations, and swimming velocities during IS compared to OS training. Despite greater physiological activation and improved performance, RPE responses were similar or slightly lower during IS compared to OS tests. These results produced a right-hand shift in the RPE-HR, RPE-La, and RPE-velocity relationships (see *Figures 3.1, 3.2,* and *3.3*), such that athletes were working harder during IS compared to OS tests without perceiving the work as any more demanding. Although some researchers have demonstrated training induced reductions in RPE relative to VO_2 (DeMello et al., 1987; Skrinar et al., 1983; Spodaryk et al., 1990) and La (Martin et al., 1999), this is the first study to show reductions in RPE in conjunction with increases in HR and La at the AT and maximal intensity as a function of state of training.

The effect of training on RPE has been examined with absolute and relative workloads, using different testing protocols, and participants of varying fitness levels. It would not be fruitful to compare the results from this study directly with studies that used dissimilar research methods. For example, participants in this study subjectively paced the incremental swims from easy to maximal. It would, therefore, be unreasonable to compare these results with studies that used absolute workloads to compare RPE responses to training. Where possible, the results from this study will be compared with research that used similar experimental designs, testing protocols, and participants.

There was little effect of training period on RPE responses. As shown in Table 3.1, the mean differences in RPE between conditions were small at low workloads, at the AT, and at maximal effort. Similar RPE responses at minute-five are expected because of the low physiological demand. Other researchers have not detected differences in RPE between trained and untrained participants when tested at low workloads (Docktor & Sharkey, 1971; Morgan & Pollock, 1977; Patton et al., 1977; Seip et al., 1991; Spodaryk et al., 1990). Some authors have questioned whether low work intensities provide sufficient physiological demand to make meaningful RPE comparisons across training periods, and that workloads need to reach a certain threshold (e.g., AT, ventilatory threshold) before central and peripheral mediators of exertion make important contributions to perceptions of effort (Cafarelli, 1977; Mihevic, 1981; Robertson, 1982).

Slightly lower RPE responses at the AT and minute-35 are inconsistent with the findings of researchers who reported increased RPE responses at the AT or 4.0 $mmol.l^{-1}$ FBLC as a function of training (Haskvitz et al., 1992; Held & Marti, 1990; Seip et al., 1991; Simon et al., 1983). The findings in this study are more similar to those of DeMello et al. (1987) who reported similar RPEs between trained and untrained participants at the LT and maximal effort. Other researchers to report decreases in RPE with training compared participants at workloads relative to percentages of VO_2max (DeMello et al., 1987; Skrinar et al., 1983; Spodaryk et al., 1990). With the exception of Held and Marti (who employed a dubious method for athlete selection, as discussed in the review of literature), these studies used non-elite participants. The perceptual responses from this study are consistent with the only other study to use elite performers to investigate RPE responses across the athletic season. Foster et al. (1999) reported the same mean RPE responses during IS and OS stages of training at the AT and maximal workloads with elite speed skaters. Given these results, it is possible that the increases in RPE at the AT following training reported by some researchers might not apply to highly trained participants.

The finding of increased HRs following training is not consistent with theoretical expectations or with some other studies that have used elite athletes to investigate the effect of training on RPE relationships (Martin et al., 1999). Typically, HRs at given relative workloads decrease or remain stable following training due to physiological adaptations, such as improved stroke volume. Although it is not clear why participants in this study had higher HRs during IS compared to OS training, early season training overloads may have resulted in fatigue-induced reductions in HR during OS tests. The OS tests were performed soon after athletes returned from an OS break, and training at this stage involved intensity overloading to build fitness from a relatively low base. Martin and Andersen (2000) found decreased HRs and slightly lower RPEs following six weeks of high intensity training. The authors found that the magnitude of decrease in HR for a given RPE was a good indicator of athletes' performance following taper, and may be indicative of training-induced fatigue and appropriate overload during training. When investigating the effects of training on RPE relationships in elite athletes, researchers may need to consider how the relationships among high intensity training, fatigue, and training overload might affect perceptual and physiological responses across the athletic season. Similar to the HR responses in this study, Foster et al. (1999) also reported a nonsignificant increase in HR at the AT from deconditioned to conditioned phases of training for elite level speed skaters.

La responses followed expected adaptations to training. Although La responses at minute-five were effectively the same, training resulted in increased La concentrations at the AT and at maximal effort. These results are consistent with the findings of previous research that demonstrated increased La thresholds (Carter, Jones, & Droust, 1999; Weltman et al., 1992) and increased maximal La concentrations following training (Fukuba et al., 1999; Jeukendrup, Hesselink, Snyder, Kuipers, & Keizer, 1992).

Training period had a medium overall effect on the HR-RPE relationship. During IS training, swimmers had higher HRs at a given RPE, but this effect varied according to workload. There was little effect at the lowest workload, which might be expected given the low levels of physiological demand (as discussed earlier). At the AT, there was a moderate to large difference in HR-RPE ratios due to slightly lower RPE responses and greater HRs from OS to IS training. The only other research to examine the effect of training on HR and RPE responses at the AT was Foster et al. (1999), who used a similar research design to examine HR, La, and RPE responses of elite level speed skaters during GXTs performed in conditioned and deconditioned periods of training. Foster et al. reported the same RPE and slightly increased HRs at the AT (4.0 $mmol.l^{-1}$) despite significantly greater power outputs following training. The results from Foster et al. are not dissimilar to the results from this study. Both studies showed training induced improvements in performance that were accompanied by slight increases in HR. Although Foster et al. reported the same mean RPE responses at the AT compared to slightly lower RPEs in this study, both these results showed lower perceptions of exertion at the AT for a given performance level (power or velocity) and HR.

The results from this study also suggest that workload had a large effect on the HR-RPE relationship in elite athletes. As shown in Table 3.2, the HR-RPE ratio decreased with increased workload, indicating that the rate of increase in RPE was greater than HR as workloads increased. Slight variations in the rate of reduction in HR-RPE ratios between tests contributed to the small interaction effect between training and workload.

Much of the effect of workload on the HR-RPE relationship occurred between stage one and the AT. Whereas HR increased by approximately 44 bpm between these points during IS and OS tests, RPE increased by around 8.5 during the IS test, and 9.0 during the OS tests. Although these responses do not follow Borg's estimation that RPE should approximate one tenth of an individual's HR, this estimate was presented as a rough approximation only. At the AT and at maximal exertion, the relationship between HR and RPE more closely approximates Borg's estimation. These results appear consistent with Borg's comments regarding the relation of RPE and HR, with the "one-tenth" rule holding for moderate exercise intensities, but less consistent for low exercise intensities (Borg, 1970, 1982). This result is consistent with the findings of Martin et al. (2000), who reported HR-RPE ratios of 14.34 and 13.88 at a HR of 150 bpm following high intensity training and taper respectively. These ratios correspond well with those presented in this study.

The choice of the AT (rather than the LT) as an important point to compare RPE relationships in elite athletes is somewhat justified because the HR-RPE relationship returns to more expected values by this point. The only other study to examine directly how the relationship between RPE and HR changes according to workload used steady-state protocols. In contrast with the results from this study, Garcin et al. (1998) reported that for a given RPE, HRs were nine percent higher between steady-state cycling performed at 86% compared to 60% of maximal aerobic power. Garcin et al. emphasised the influence of exercise duration on RPE relationships and reported that, during constant load exercise, HR can increase without any change in RPE. These results highlight the difficulty of comparing RPE relationships between studies that use steady-state and incremental protocols, or between studies that use incremental protocols with varied stage durations.

Training period had a large overall effect on the La-RPE relationship, with athletes exhibiting higher La concentrations at a given RPE during IS compared to OS training. Training period had a greater overall effect on the La-RPE than the HR-RPE relationship, and similarly, this effect varied according to workload. As workloads increased the effect of training on the La-RPE relationship became progressively greater. There was essentially no effect at the lowest workload from OS to IS tests for RPE (0.25 increase) and La (0.12 $mmol.l^{-1}$ decrease). These results are consistent with the results obtained for HR-RPE and, as discussed earlier, is consistent with theoretical expectations that changes in RPE relationships as a function of state of training are unlikely to be detected at low workloads. At the AT, small increases in La and small decreases in RPE from OS to IS training represented only a .02 mean difference in La-RPE. Although this resulted in a small to medium effect according to Cohen's *d*, this can be mostly attributed to the extremely small variation La-RPE between participants (see standard deviations presented in Table 3.2) and it is questionable whether such a small mean difference represented any meaningful or generalisable effect. At the highest workload, increases in La and decreases in RPE from OS to IS training represented a medium effect for La-RPE. These results are illustrated in *Figure 3.2*, which shows changes in the relationship between La and RPE at higher workloads. Other researchers that examined La-RPE relationships in elite performers have shown that La-RPE ratios decrease during a period of exhaustive training, suggesting that La-RPE ratios can be used to monitor fatigue induced by overtraining (Garcin et al., 2002; Snyder et al., 1993). In this regard, the results from this study suggest that the participants were unlikely to be overtrained when IS testing was conducted.

Overall, these results suggest that, at higher exercise intensities, RPE was lower at a given La concentration as a function of improved state of training. These results are inconsistent with the findings of other researchers who reported that RPE remains stable at FBLCs greater than the LT (Steed et al., 1994) and that the relationship between La and RPE is not affected by training (Foster et al., 1999; Seip et al., 1991; Simon et al., 1983). In support of the findings in this study, Spodaryk et al. (1990) found slightly lower RPE responses but greater La concentrations at high (75% and 90% of VO_2max) but not low workloads for trained compared to untrained women. In addition, Boutcher et al. (1989) reported training induced reductions in RPE at the LT. Martin et al. (1999) reported slight increases in RPE and large increases in La upon completion of a 30TT in response to training. In agreement with the results of this study, lower RPE responses were found for a given La concentration. The results from this study, and that by Martin et al., suggest that adaptations to high intensity training may allow elite athletes to sustain higher La concentrations relative to perceptions of exertion. Although the effect of training on the La-RPE relationship in this study were descriptively large, the nonsignificant result means that the reliability of this finding needs to be tested using more powerful investigations with a greater number of participants.

The results from this study also suggest that workload has a large effect on the La-RPE relationship in elite athletes. As shown in Table 3.2, the La-RPE ratio increased with increases in workload. The increases in the La-RPE relationship with increased exercise intensity follow expected changes in La and RPE that have exponents of 2.5 and 1.0, respectively, with workload (Borg et al., 1987). The exponential relationship between La accumulation and workload helps explain the particularly large increase in the La-RPE ratio between the AT and maximal intensity. This large increase also occurs because, by definition, the AT marks the workload at which a rapid rise in La occurs (whereas RPE should still increase linearly with workload). The large interaction effect reported in Table 3.3 suggests some variation in the increase in La-RPE ratios between IS and OS training. Table 3.3 shows that La increases at a greater rate in relation to RPE during IS compared to OS tests. This is likely the result of the higher performance capabilities of athletes during IS training and the greater range of La concentrations obtained during IS tests (see Table 3.1).

The small and homogenous sample limits the generalisation of these findings. Small sample sizes, however, characterise much of the research examining the effect of training on RPE. Unlike other research findings, and consistent with the recommendations of several professional associations (e.g., American Psychological Association), the results from this study are presented as effect sizes. Nonsignificant results sometimes represent potentially meaningful effects in terms of the magnitude of difference between groups or the percentage of variance accounted for by group membership. As reported in the literature review, some researchers (e.g., Haskvitz et al., 1992) report nonsignificant results as representing no difference when meaningful differences exist (suggestive of a Type II error). In addition, other researchers have relied upon statistical significance testing with small sample sizes and have not provided the additional information (e.g., means, standard deviations) from which effect sizes could be calculated.

Conclusion

The results from this study suggest that the relationships between RPE and HR, and RPE and La were altered in highly trained participants from OS to IS periods of training. Changes in RPE relationships were only evident at higher exercise intensities. Although these results are inconsistent with some research (DeMello et al., 1987; Held & Marti, 1999), the finding of lower RPEs for given HR and La responses following training are supported by recent research involving elite cyclists during a 30TT (Martin et al., 1999).

These findings challenge the notion (established on the basis of non-elite participants) that state of training does not alter RPE relative to HR or La (DeMello et al., 1987; Ekblom & Goldbarg, 1971; Haskvitz et al., 1992; Seip et al., 1991). The results from this study are distinctive because, rather than separately examine RPE and physiological responses at fixed workloads or levels of physiological demand (e.g., the LT, FBLCs, the ventilatory threshold, percentage of VO_2max), this study investigated the effect of training on the *relationship* between RPE and physiological parameters during incremental exercise by using the ratio between RPE and physiological variables.

RPE is routinely used to monitor training adaptations in elite athletes, yet much of the research conducted to investigate the effects of training on RPE have used previously sedentary or non-elite participants. The characteristics of high intensity training (e.g., training intensity overloads, exercise duration, training frequency) may alter the perceptual interpretation of physiological mediators of RPE. Specifically, the results from this study suggest that athletes are able to attain better performance outcomes, higher cardiac frequency, and greater La concentrations during IS compared to OS training while perceiving the exercise as no more demanding.

CHAPTER 4

A COMPARISON OF HEART RATE-RPE AND LACTATE-RPE RELATIONSHIPS IN ELITE CYCLISTS IN HOT AND MODERATE ENVIRONMENTAL TEMPERATURES

Method

Participants

Members of the Australian Road Cycling Team ($N = 12$) participated in this study. Participants were aged between 18 and 32, all competed at the elite level, and included three professional cyclists, two junior time-trial world championship competitors, and two competitors in the Commonwealth Games.

Measurement

For a description of HR, La, and RPE measures used in this study see the *Measurement* section of Chapter 3.

Procedure

Each participant completed one VO_2max and two 30-minute time trials (30TT) over six days. The VO_2max test was performed on day 1 and the time-trials were performed on days 4 and 6. The VO_2max test and one 30TT were performed in moderate conditions (23°C and 58% relative humidity) and the other time trial was performed in hot conditions (32°C and 60% relative humidity).

The VO_2max test was performed using the Lobe Excaliber electromagnetically braked bicycle (Lobe BV Groningen, The Netherlands). The protocol started at 100 W with the resistance increasing 50 W in stages every five minutes until voluntary exhaustion. Capillary blood samples were taken immediately before the trial and every five minutes throughout the trial. HR was monitored throughout the test and recorded upon completion of each five-minute stage. Participants were asked verbally to rate their perceived exertion on the RPE scale during the last 10 seconds of each stage just before the next 50 W resistance increase.

From the La curve obtained during the VO_2max test, the power output that corresponded to each participant producing 4.0 $mmol.l^{-1}$ of La was used to set individual workloads during the subsequent steady-state time trials. This level was predicted to be the average power output the cyclists could maintain over a 30TT. Participants' desired cadences were coupled with predicted power outputs to produce a linear factor value that was used to set the resistance of the Lobe Excaliber. Prior to the 30TT commencing, cyclists performed a 10–15 minute warm-up using their bicycles attached to wind-trainers. The cyclists were instructed to complete the 30TT with the highest average power possible and were reminded to treat the test as they would a real competitive effort. The time trials were performed in an environmental chamber that works on a feedback mechanism using a proportional integrating differential control. The desired temperature and humidity were set on a computer, monitored by sensors within the chamber, and adjusted constantly to meet desired conditions. Every five minutes capillary blood sample were taken and participants were asked to verbally rate their perceived exertion. HR was measured throughout the trials and recorded every five minutes.

Data Analysis

The variables of power output, HR, and La were plotted against RPE over the duration of the time trials performed in moderate and hot conditions. To examine further the relationship between RPE, HR, and La, ratios between RPE and HR and RPE and La were compared between tests performed in hot and moderate conditions. HR-RPE and La-RPE ratios were calculated for each participant at minute-10, minute-20, and minute-30 of the time trials. Within groups 2 (temperature) x 3 (time) ANOVAs were used to assess differences in RPE ratios at minute-10, minute-20, and at minute-30 of the time trials between test conditions (hot and moderate temperatures). Interactions and main effects for condition and time are reported in terms of significance tests ($p < .05$) and effect sizes (η^2). The magnitudes of difference (Cohen's *d*) for RPE ratios at minute-10, minute-20, and at minute-30 between trials performed in hot and moderate conditions are also reported. For a justification of statistical analyses see *Data Analysis* in Chapter 3.

Results

Table 4.1 presents the means and standard deviations for RPE, HR, and La at minute-10, 20, and 30 of the 30TTs performed in hot and moderate conditions. *Figure 4.1* describes the relationship between RPE and HR during these trials and shows that athletes had higher HR and RPE responses during trials performed in hot compared to moderate conditions. *Figure 4.2* describes the relationship between RPE and La for moderate and hot temperature time trials. These results show that La concentrations were greater in the hot condition for the first 15 minutes of the time trial but considerably lower during the last 15 minutes. Despite this variability in La, RPE responses were consistently higher in the hot condition. *Figure 4.3* compares power outputs at a given RPE between trials performed in hot and moderate conditions. After the first five minutes of exercise average power outputs relative to RPE responses were notably lower in the hot condition compared to the moderate temperature condition.

Table 4.1

Means and Standard Deviations for RPE, HR, and La for Time Trials Performed in Hot and Moderate Temperatures.

Minute	RPE				HR				La			
	Moderate		Hot		Moderate		Hot		Moderate		Hot	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
10	14.88	1.42	15.38	1.58	178.83	7.35	182.42	8.80	5.29	1.70	6.63	2.25
20	16.25	1.12	17.25	0.75	184.00	6.08	186.17	10.58	6.00	1.14	5.47	2.24
30	19.04	0.75	19.04	0.33	196.08	8.86	195.17	12.40	10.08	2.12	6.89	2.52

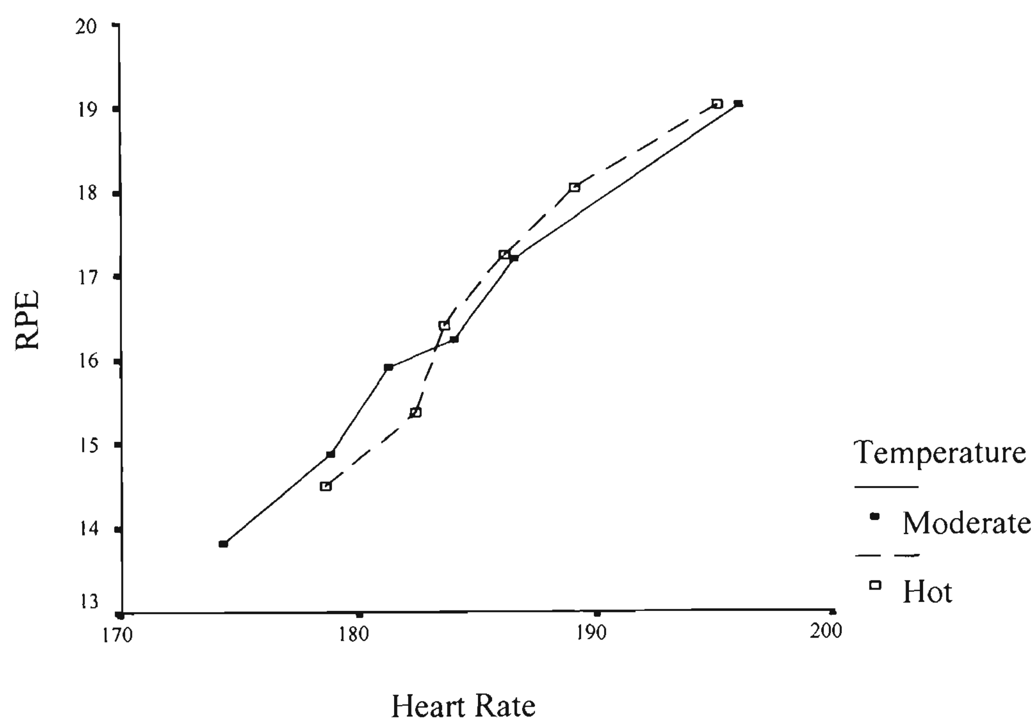

Figure 4.1. Variation in RPE with HR during time trials performed in moderate and hot temperatures.

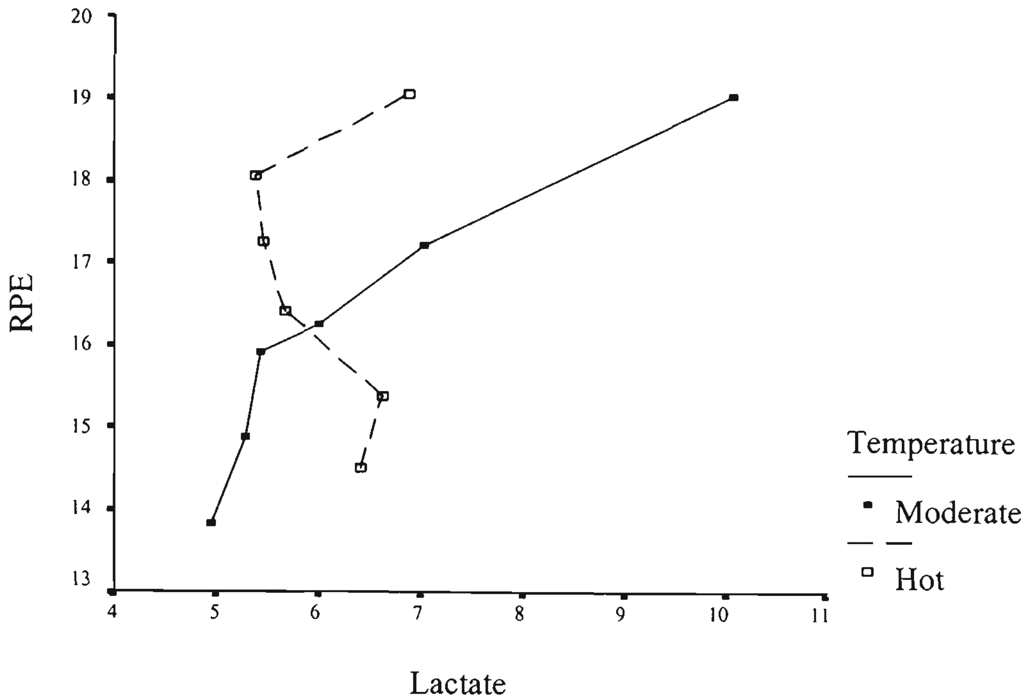

Figure 4.2. Variation in RPE with La during time trials performed in moderate and hot temperatures.

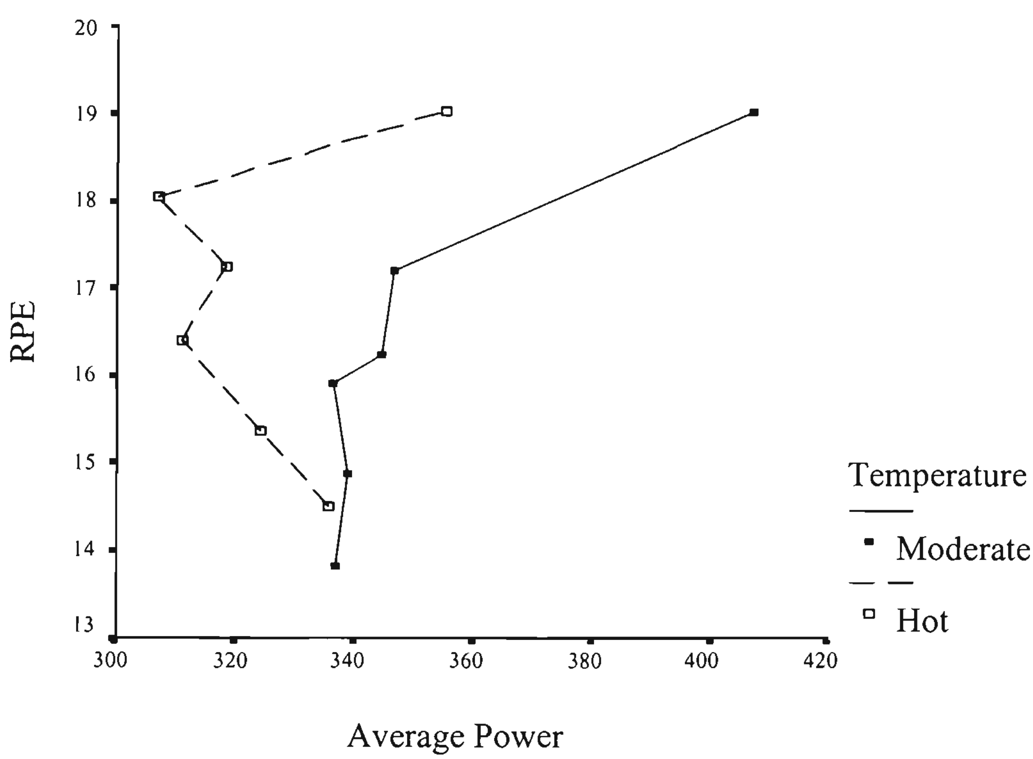

Figure 4.3. Variation in RPE with power output during time trials performed in moderate and hot temperatures.

Ratios between HR and RPE, and La and RPE were calculated every ten minutes throughout the trials for each participant to determine differences in RPE relationships between time trials performed in moderate and hot temperatures. Table 4.2 presents the means and standard deviations for HR-RPE and La-RPE ratios during each time trial. Table 4.3 shows the results of the within-groups ANOVAs for HR-RPE and La-RPE ratios across minute-10, 20, and 30 of the 30TTs performed in hot and moderate conditions.

Table 4.2

Means and Standard Deviations for HR-RPE and La-RPE Ratios During Time Trials Performed in Hot and Moderate Temperatures.

Minute	HR-RPE				La-RPE			
	Moderate		Hot		Moderate		Hot	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
10	12.13	1.29	11.98	1.35	0.37	0.11	0.43	0.16
20	11.38	0.95	10.81	0.75	0.37	0.07	0.32	0.13
30	10.35	0.67	10.25	0.69	0.53	0.10	0.36	0.13

Table 4.3

F-values, df, Significance Levels, and Effect Sizes Comparing RPE Ratios Between Time Trials Performed in Hot and Moderate Temperatures.

Source	HR-RPE					La-RPE				
	F-value	*df*	*p*	η^2	Power	*F*-value	*df*	*p*	η^2	Power
Temperature	1.32	1.00	> .05	.11	.18	2.73	1.00	> .05	.20	.33
Time	30.14	1.42	< .05	.73	1.00	13.55	1.19	< .05	.55	1.00
Interaction	1.33	1.73	> .05	.11	.39	11.69	1.75	< .05	.52	.88

There was a significant main effect for time on the HR-RPE relationship. This result represented an extremely large effect ($\eta^2 = .73$), with HR-RPE ratios decreasing with time (as indicated in Table 4.2). Results showed a medium to large effect of temperature ($\eta^2 = .11$) and a medium to large interaction effect of temperature and time ($\eta^2 = .11$) on the HR-RPE relationship, although the small sample size contributes to a lack of statistical significance. An examination of the magnitude of differences in the HR-RPE relationship between hot and moderate conditions at different time points showed little difference at minute-10 ($d = 0.11$), a medium to large difference at minute-20 ($d = 0.62$), and a small difference at minute-30 ($d = 0.18$). These results represented a 22 percentile point shift in HR relative to RPE at minute-20 and a 7 percentile point shift in HR relative to RPE at minute-30.

There was a significant main effect of time on the La-RPE relationship. This result represented an extremely large effect ($\eta^2 = .55$), with the La-RPE ratio remaining the same between minute-10 and minute-20 in the moderate condition before increasing by minute-30. In the hot condition the relationship between RPE and La was less consistent, with the La-RPE ratio being greatest at minute-10, decreasing at minute-20, and increasing at minute-30 (see Table 4.2). Results showed a large effect of temperature ($\eta^2 = .20$) on the La-RPE relationship, although the small sample size contributes to a lack of statistical significance. A significant and extremely large interaction effect between temperature and time was detected for the La-RPE relationship ($\eta^2 = .52$). An examination of the magnitude of differences in the La-RPE relationship between hot and moderate conditions at different times showed a moderate difference at minute-10 ($d = 0.48$), a moderate difference at minute-20 ($d = 0.54$), and an extremely large difference at minute-30 ($d = 1.05$). These results represented a 18 percentile point shift in La relative to RPE at minute-10, a 21 percentile point shift in La relative to RPE at minute-20, and a 44 percentile point shift in La relative to RPE at minute-30.

Discussion

The results from this study should be considered novel because they were obtained during self-paced 30TT testing. Although target power outputs were provided to participants, this test was not a true steady-state trial because athletes self-pace their work and adjust cycling intensities to complete the trial with the greatest average power output possible. The power outputs used at the commencement of the tests were not intended to be maintained over the duration of the trial, rather, they were a reference point so the cyclists could quickly settle into an appropriate pacing strategy. As shown in *Figure 4.3*, this protocol resulted in variations in the power output produced throughout the test. Although offering interesting information about how elite athletes pace their performance in different environmental temperatures, the results obtained in this study are not readily compared with previous research that investigated the effect of environmental temperature on RPE relationships using GXTs or steady-state protocols where power outputs remained stable throughout testing.

The perceptual and physiological responses reported in this study should be examined in relation to the different workloads performed in hot compared to moderate ambient temperatures (see *Figure 4.3*). At minute-5, athletes were able to maintain comparable power outputs between conditions but provided greater RPE responses in the hot condition. This result suggests that high ambient temperatures are associated with greater perceptions of exertion early during exercise tests and independent of exercise intensity. High ambient temperatures also resulted in a reduction in workloads in accordance with the goals of the test (i.e., achieving the greatest average power output over the test duration). Despite lower workloads, RPE responses progressively increased with exercise time and were consistently greater at comparable time points in the hot temperature condition. These results suggest that the athletes were pacing themselves in the hot condition according to their perceptions of effort, independent of workload and La (as discussed later in this chapter). The progressive increases in RPE in both conditions, and greater RPEs and lower power outputs in the hot condition, suggest that RPE in high ambient temperatures was likely to be governed by accumulated exercise time and greater fatigue induced by hot temperatures. These results are inconsistent with some previous research findings that demonstrated no increase in RPE in hotter conditions at the same steady-state power outputs (Glass et al., 1994; Pandolf et al., 1972). These results might be attributed to the effect of high workloads on core body temperature that will be addressed later in this discussion.

The hot temperature condition resulted in greater HRs at comparable time points aside from minute-30. These results are consistent with previous research findings that reported increased exercise HRs at high ambient temperatures (Sawka & Wenger, 1988). The increases in HR in hot conditions found in this study, however, were less than in previous RPE research (e.g., Bergh et al., 1986; Galloway & Maughan, 1997; Glass et al., 1994). Smaller increases in HR at minute-10 and 20, and lower HRs at minute-30 in hot compared to moderate temperatures were likely the result of decreased power outputs obtained during cycling in the hot condition (*Figure 4.3)*.

Due to the self-paced protocol and the performance-related objectives of the 30TT, La responses in the hot condition were not consistent across time. As shown in *Figure 4.2*, athletes demonstrated elevated La concentrations early during 30TTs in the hot condition. The changes in La tended to track changes in power output for the duration of the test. Although previous research findings suggest that high ambient temperatures result in elevations in La during exercise (Nadel, 1983), such increases have not been shown at rest or during the early stages of exercise tests (Parkin, Carey, Zhoa, & Febbraio, 1999; Young, Sawka, Levine, Cadarette, & Pandolf, 1985). Participants in this study, however, performed a 10–15 minute warm-up prior to the 30TTs. It is possible that factors that contribute to high La concentrations during exercise in hot conditions (e.g., increased skin blood circulation, decreased local muscle circulation, local muscle hypoxia, increased serum glucose, increased anaerobic glycolysis) may have been initiated during warm-up and subsequently came into play early in the 30TT. Gregson, Drust, Batterham, and Cable (2002) did not find differences in La or blood glucose between active warm-up, passive warm-up, and no warm-up conditions in moderate temperatures, but the effects of active warm-up in high ambient temperatures have not been investigated. The high initial power output (corresponding to the AT) may also have contributed to the early elevation of La during the 30TT in the hot condition in this study.

The relative magnitude of increase in RPE and HR from tests performed in moderate and hot ambient temperatures resulted in lower HR-RPE ratios in the hot condition at minute 10, minute 20, and minute 30 (see Table 4.2). As presented in Table 4.3, these outcomes resulted in a moderate to large overall effect of temperature on the HR-RPE relationship. The size and direction of the effect of ambient temperature on HR-RPE varied across exercise time. Athletes had higher HRs for a given RPE during the early stages of the 30TT, but lower HRs for a given RPE from minute-15 onwards in hot temperatures (see *Figure 4.1*). Although the early HR-RPE responses are consistent with previous research findings (Bergh et al., 1986; Glass et al., 1994; Maw et al., 1993; Pandolf et al., 1972), the HR-RPE responses found during the later stages of the 30TT are not found in previous research and are the result of increased RPE responses in hot temperatures. This perceptual response may have occurred because of the high performance capabilities of the elite athletes participating in this study. Thermoregulatory responses hypothesised as possible mediators of exertion (e.g., sweat rate, blood flow) are dependent upon a threshold increase in core body temperature (Sawka & Wenger, 1988). Core body temperature has long been established as dependent upon metabolic rate and not ambient temperatures (Armstrong & Pandolf, 1988). It is possible that the high workloads performed by elite athletes in this study contributed to increases in the metabolic rate and may have resulted in increased core body temperature during the later stages of the test. Subsequent increases in sweat rate and skin blood flow may have resulted in increased RPE in hot conditions not found in participants working at lower exercise workloads. Researchers who used greater exercise intensities and durations and demonstrated increases in core body temperature also reported heat induced increases in RPE during exercise tests (Galloway & Maughan, 1997). This possible interaction between high intensity exercise, core body temperature, and RPE is of particular interest in light of recent research that identified core body temperature and EEG frequencies over the frontal cortex (and not EMG indicators of muscle activity patterns) as the best predictors of RPE responses to hyperthermia (Nybo & Nielson, 2001).

The results from this study also suggest that exercise time has a large effect on the HR-RPE relationship. As shown in Table 4.2, the HR-RPE ratio decreased with increased exercise time. This result is consistent with the findings from Study 1 that showed decreased HR-RPE ratios with increased workload. These results suggest RPE grows at a greater rate in relation to HR as exercise workloads and accumulated exercise time increase. These results can be partly attributed to the low RPEs early during exercise tests, with perceptual responses increasing from a low base. Small variations in the rate of reduction of the HR-RPE ratios between test conditions contributed to the large but nonsignificant interaction effect between temperature and time.

Ambient temperature had a large overall effect on the La-RPE relationship (see Table 4.3). The variations in La responses discussed earlier resulted in inconsistencies in the La-RPE relationship over time. Early elevations in La during the initial stages of the hot temperature trial resulted in greater La concentrations for a given RPE during the first 10 minutes of cycling in this condition. Reduced La concentrations (consistent with reduced power outputs) and progressive increases in RPE during the middle stages of the test resulted in lower La concentrations for a given RPE for the remainder of the 30TT in the hot compared to the moderate condition (see *Figure 4.2*). These responses resulted in large fluctuations in the La-RPE ratio (see Table 4.2), and suggest that the La-RPE and power-RPE relationships break down in hot conditions for elite athletes during self-paced 30TTs. As discussed earlier, this result might be attributable to the high exercise intensities performed by elite athletes during testing and the effect high workloads have on core and skin temperatures. Further, the progressive increase in RPE over the trial duration suggests that the athletes were pacing themselves according to their perceptions of exertion (despite the lack of relation of RPE with La and power). Although clearly being able to sustain higher power outputs and La concentrations during the trial (as shown in the moderate temperature condition), the greater perceptions of exertion and feelings of fatigue induced by high workloads and high ambient temperatures resulted in the athletes reducing their workloads to a level perceived as sustainable over 30 minutes.

Although the results from this study show that exercise time has a large effect on the La-RPE relationship, the trend shown in Study 1 (i.e., increased La-RPE ratios with increased workload) was only evident in the moderate temperature condition. The different trends for La-RPE over time between tests performed in hot and moderate conditions are also indicated by the large and statistically significant interaction effect between temperature and time. In the moderate condition, the La-RPE ratio was the same at minute-10 and 20, but considerably larger by minute-30. Again, given the different exponents for the La-workload and RPE-workload relationships (see discussion for Study 1), increases in La-RPE ratio with increased exercise time is expected. The La-RPE relationship did not show a consistent trend over time in the hot condition. As shown in Table 4.2, the La-RPE ratio was greatest at minute-10, decreased by minute-20, before increasing by minute-30. This pattern can again be attributed to the self-paced exercise protocol and reductions in the power output performed by athletes during the middle stages of the 30TT that resulted in reductions in La (see *Figure 4.2*). This result suggests that La and power output were not primary cues for perceived exertion during 30TTs in the hot condition, and accumulated exercise time and greater fatigue induced by higher ambient temperatures were more closely related to RPE.

Conclusion

Although the results from this study are not directly comparable to research that used steady-state or GXT protocols, consistent with previous findings, the results do show that high ambient temperatures alter RPE relationships. Alterations in the HR-RPE and La-RPE relationships in this study are related to the self-paced protocol used, and reductions in power output during the middle stages of the 30TT performed in the hot condition. The results show that high ambient temperatures contribute to perceptions of exertion for elite cyclists during a 30TT, and physiological and performance parameters tend to be lower for given RPEs during tests performed in hot compared to moderate temperature conditions.

CHAPTER 5

A COMPARISON OF HEART RATE-RPE AND LACTATE-RPE RELATIONSHIPS IN ELITE CROSS COUNTRY SKIERS IN SIMULATED ALTITUDE AND SEA LEVEL CONDITIONS

Method

Participants

Members of the men's Australian Cross-Country Ski Team ($N = 9$) participated in this study. The participants were aged between 20 and 29 and, although considered elite by Australian standards, none of were ranked in the top 50 in the world.

Measurement

For a description of HR, La, and RPE measures used in this study see the *Measurement* section of Chapter 3.

Procedure

Each participant performed two incremental ski-striding treadmill tests in simulated sea level and altitude (1800 m) conditions. At an ambient barometric pressure of 710 mmHg in Canberra (600 m altitude), sea level and 1800m altitude conditions were simulated with 22.4% (enriched O_2) and 18.1% (enriched N_2) inspired O_2, respectively. The test protocols involved participants walking on a treadmill using ski poles that have rubber stoppers covering the metal tips. Participants were familiar with the test protocols prior to testing. The duration of the first stage of the treadmill test was four minutes, and the duration of all subsequent stages was three minutes and 45 seconds. Participants rested for 45 seconds between each workload. The first treadmill stage was conducted at a six percent grade at six km.hr^{-1}. Gradient was increased two percent and speed increased by 0.5 km.hr^{-1} at each subsequent stage. Time, gradient, and treadmill speed are presented in Table 5.1. Skiers were encouraged to walk for as long as possible using long strides. Skiers later engaged in hill-bounding as they attempted to maintain the required speed and achieve maximal performance. Skiers were encouraged to stay on the treadmill as long as possible. The test was terminated when participants could no longer maintain the required workload. Maximal perceptual and physiological responses were obtained from the final completed stage.

Table 5.1.

Ski-Striding Treadmill Protocol.

Stage	Time (min:sec)	Grade (%)	Speed ($km.hr^{-1}$)
1	00:00 - 04:00	6.0	6.0
Rest	04:01 - 04:45		
2	04:46 - 08:00	8.0	6.5
Rest	08:01 - 08:45		
3	08:46 - 12:00	10.0	7.0
Rest	12:01 - 12:45		
4	12:46 - 16:00	12.0	7.5
Rest	16:01 - 16:45		
5	16:46 - 20:00	14	8.0
Rest	20:01 - 20:45		
6	20:46 - 24:00	16	8.5
Rest	24:01 - 24:45		
7	24:46 - 28:00	18	9.0
Rest	28:01 - 28:45		
8	28:46 - 32:00	20	9.5

At the completion of each work stage a capillary blood sample was taken from the fingertips using the capillary puncture method and athletes were shown the RPE scale and asked to verbally rate their overall exertion. HR was monitored throughout the ski-striding protocols and recorded immediately upon completion of each test stage.

Data Analysis

The variables of HR and La were plotted against RPE during ski-striding treadmill tests performed at altitude and at sea level. To examine further the relationship between RPE, HR, and La, ratios between RPE and HR and RPE and La were compared between altitude and sea level tests. HR-RPE and La-RPE ratios were calculated for each participant at low intensity (stage one), the AT, and at high intensity workloads (90% of maximum work time) during each treadmill test. Because participants could not attain equivalent maximal workloads during tests performed at altitude compared to sea level, perceptual and physiological comparisons at high intensities were made at an equivalent percentage (90%) of maximum work time. Within groups 2 (altitude) x 3 (time) ANOVAs were used to assess differences between simulated sea level and altitude tests for RPE ratios at stage one, the AT, and 90% of maximum work time. Interactions and main effects for workload and altitude are reported in terms of significance tests ($p < .05$) and effect sizes (η^2). The magnitude of difference (Cohen's *d*) for RPE ratios at stage one, the AT, and 90% of maximum work time between simulated sea level and altitude tests are also reported. For a justification of statistical analyses see Chapter 3.

The AT was calculated according to the modified D-max method. For a description of this calculation and the methods used to obtain D-max, see Chapter 3.

Results

Table 5.2 presents means and standard deviations for RPE, HR, and La responses at stage one, the AT, and 90% of maximum work time for incremental ski-striding treadmill tests performed in acute altitude and sea level conditions. *Figure 5.1* illustrates the relationship between RPE and HR during treadmill tests performed in altitude and sea level conditions. Differences in HRs were mostly negligible. RPE responses were greater in the altitude condition, but differences between conditions became smaller as workloads increased and were negligible at the AT and maximal workloads. *Figure 5.2* shows the relationship between La and RPE between altitude and sea level conditions. At low workloads and at the AT, La did not vary meaningfully between altitude and sea level testing. At stage 1, La responses were similar between conditions, but became progressively greater during tests at sea level compared to altitude as workloads increased.

Table 5.2

Means and Standard Deviations for RPE, HR, and La During Incremental Ski Striding Treadmill Tests Performed in Simulated Altitude and Sea Level Conditions.

Stage	RPE				HR				La			
	Altitude		Sea Level		Altitude		Sea Level		Altitude		Sea Level	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	8.44	1.51	7.67	1.00	110.11	8.45	114.33	12.06	1.07	0.18	1.14	0.28
AT	13.83	1.25	13.50	2.15	176.22	7.16	177.78	9.94	4.14	0.87	4.49	0.97
90% work time	18.16	1.31	18.07	1.08	189.67	7.26	191.44	8.49	10.64	2.36	11.30	2.57

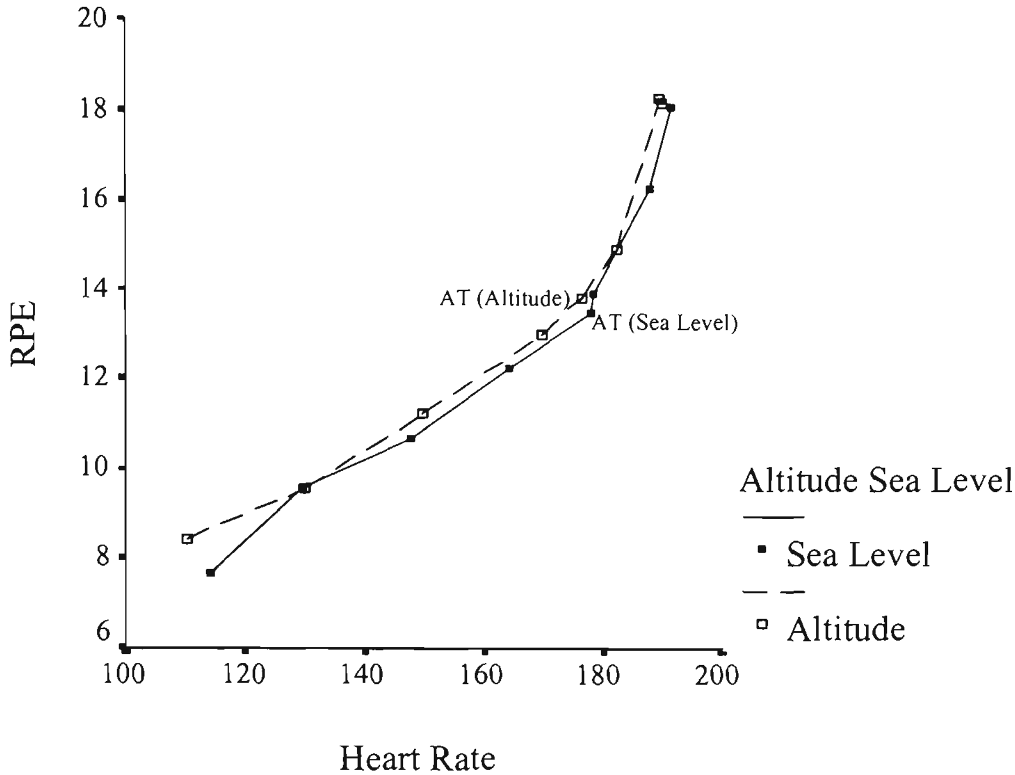

Figure 5.1. Variation in RPE with HR during altitude and sea level incremental ski striding treadmill tests.

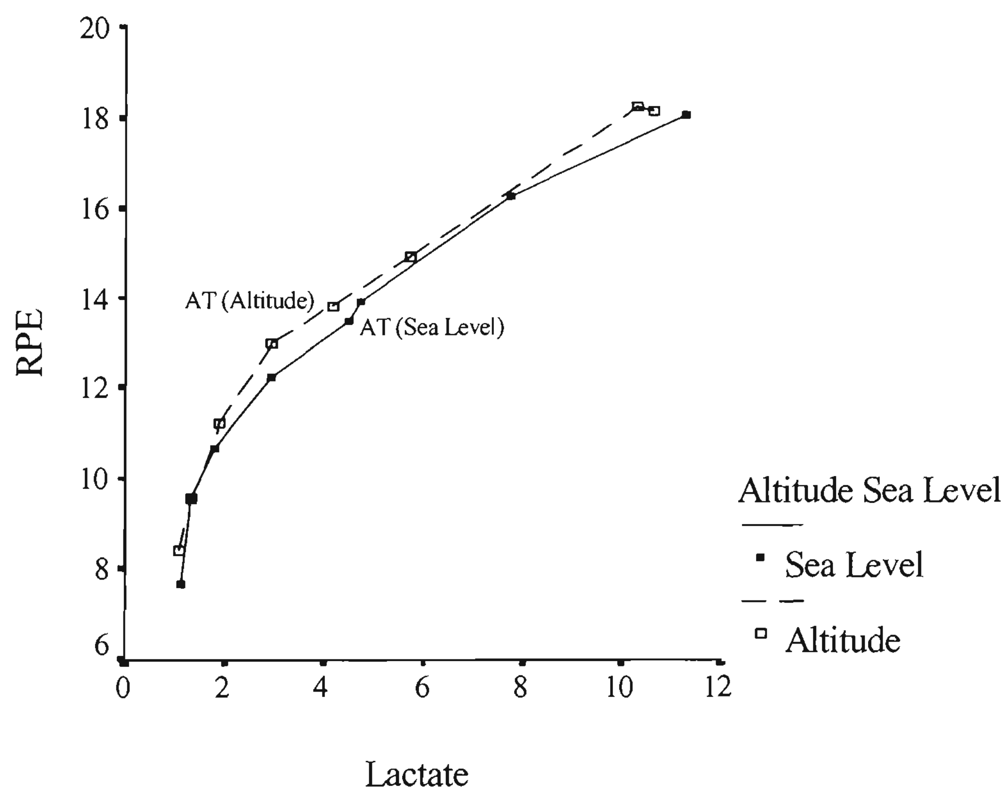

Figure 5.2. Variation in RPE with La during altitude and sea level incremental ski striding treadmill tests.

Table 5.3 presents the means and standard deviations for HR-RPE and La-RPE ratios at stage 1, the AT, and at 90% of total work time for incremental ski-striding tests in altitude and at sea level conditions. Table 5.4 shows the results of the within-groups ANOVAs for HR-RPE and La-RPE ratios across three workloads for tests performed in altitude and sea level conditions.

Table 5.3

Means and Standard Deviations for HR-RPE and La-RPE Ratios During Incremental Exercise Tests Performed in Simulated Altitude and Sea Level Conditions.

Time/ Stage	HR-RPE				La-RPE			
	Altitude		Sea Level		Altitude		Sea Level	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	13.28	1.73	15.10	2.30	0.13	0.04	0.15	0.04
AT	12.83	1.28	13.43	1.93	0.30	0.08	0.34	0.08
90% work time	10.50	0.92	10.61	0.33	0.58	0.11	0.63	0.13

Table 5.4

F-values, df, Significance Levels, and Effect Sizes Comparing RPE Ratios Between Graded Exercise Tests Performed at Altitude and Sea Level.

Source	HR-RPE					La-RPE				
	F-value	*df*	*p*	η^2	Power	*F*-value	*df*	*p*	η^2	Power
Altitude	4.69	1.00	$p > .05$	.37	.48	1.34	1.00	$p > .05$	.14	.18
Workload	20.87	2.00	$p < .05$	.72	.97	211.48	1.26	$p < .05$	.96	1.00
Interaction	2.29	1.79	$p > .05$	.22	.24	0.98	1.62	$p > .05$	.11	.18

There was a significant main effect of workload on the HR-RPE relationship. This result represented a large effect ($\eta^2 = .72$), with HR at a given RPE decreasing with increases in workload (as indicated in Table 5.2). Results showed a large effect of altitude

($\eta^2 = .37$) and a large interaction effect of altitude and workload ($\eta^2 = .22$) on the HR-RPE relationship, although the small sample size contributes to a lack of statistical significance. An examination of the magnitude of differences in the HR-RPE relationship between altitude and sea level tests at different workloads showed a large difference at stage 1 ($d = 0.78$), a medium difference at the AT ($d = 0.42$), and little difference at 90% of total work time ($d = 0.12$). These results represented a 28 percentile point shift in HR relative to RPE at stage 1, a 16 percentile point shift in HR relative to RPE at the AT, and a five percentile point shift in HR relative to RPE at 90% of total work time.

There was a significant main effect of workload on the La-RPE relationship. This result represented an extremely large effect ($\eta^2 = .96$), with La at a given RPE increasing with increases in workload (as indicated in Table 5.2). Results showed a large effect of altitude ($\eta^2 = .14$) and a medium to large interaction effect of altitude and workload ($\eta^2 = .11$) on the La-RPE relationship, although the small sample size contributes to a lack of statistical significance. An examination of the magnitude of differences in the La-RPE relationship between altitude and sea level tests at different workloads showed little difference at stage 1 ($d = 0.04$), a medium to large difference at the AT ($d = 0.63$), and a small to medium difference at 90% of total work time ($d = 0.30$). These results represented a 2 percentile point shift in La relative to RPE at the stage 1, a 24 percentile point shift in La relative to RPE at the AT, and a 12 percentile point shift in La relative to RPE at 90% of total work time.

Discussion

The results from this study suggest that acute exposure to a moderate altitude condition had some affect on the HR-RPE and La-RPE relationships in elite Australian cross-country skiers. Athletes exhibited slightly lower HR and La responses, but slightly higher RPE responses at low workloads, the AT, and high workloads (90% of total work time) during tests performed in altitude compared to sea level conditions. As shown in *Figures 5.1* and *5.2*, these responses generally resulted in slightly higher RPE responses for a given HR or La concentration at altitude. Although divergent physiological and perceptual responses contributed to some notable effect sizes between conditions (see Table 5.4), the mean differences for RPE, HR, and La at most workloads were small (see Table 5.2). The small differences in physiological and perceptual responses suggest that the moderate altitude condition used in this study might not have provided sufficient impairment of exercise capacity compared to high altitude conditions used in some previous research. It is difficult to make direct comparisons between these results and the results from other investigations of RPE at altitude. Previous research designs involved higher simulated altitude conditions, mostly adjusted workloads according to reductions in VO_2max at altitude, often concentrated on respiratory responses, and usually incorporated additional conditions (e.g., chronic altitude exposure) or groups (e.g., moderate and low altitude natives). Generally, the finding in this study of lower physiological and greater perceptual responses during exercise at altitude is not supported by previous research.

Small increases in RPE responses during tests performed at altitude compared to sea level were detected at low workloads, but at the AT and high workloads differences in RPE responses were negligible (see Table 5.2). Comparable RPE responses at the AT between tests at altitude and sea level provide support for the contention that La inflection points are important anchors for perceptions of exertion (Boutcher et al., 1989; DeMello et al., 1987; Mihevic, 1981; Pandolf, 1982; Seip et al., 1991). Similar RPE responses between exercise tests performed at altitude and sea level are consistent with results reported by Young et al. (1982) who found nonsignificant reductions in RPE during exercise in an acute high altitude condition (although low statistical power and poor reporting of results obfuscates a meaningful comparison with these results). Direct comparisons between these studies is also difficult because of different experimental conditions (high versus moderate altitudes) and different methods for determining relative workloads (percentage of VO_2max versus AT and percentage of maximal work time). These differences might account for the small reductions in RPE reported by Young et al. in comparison to the small increases reported in this study. Horstman et al. (1979) also reported reductions in RPE under similar experimental conditions used by Young et al. The RPE responses from this study are similar to those reported by Maresh et al. (1993) who found no differences in RPE between resident and high altitude conditions for participants unaccustomed to high altitudes. The only studies to show increases in RPE during exercise in acute altitude conditions were Maresh et al. (1988) and Robinson and Haymes (1990) who used moderate altitudes and absolute exercise intensities respectively. The differences in magnitude and direction of perceptual responses between studies are possibly related to different altitude conditions and different determinations for workload comparisons (i.e., lactate thresholds, percentage of total work time, absolute workloads, percentage of VO_2max). Lower RPEs were found at high altitudes and at altitude specific percentages of VO_2max, whereas similar or increased RPEs were found at moderate altitudes, unadjusted workloads, or, in this study, workloads relative to lactate accumulation or exercise time.

At low workloads, HRs were slightly lower at altitude compared to sea level, but at the AT and at 90% of maximal work time differences in HR between conditions were negligible (see Table 5.2). At absolute workloads beyond stage 1 of the exercise tests, however, HRs were slightly greater at altitude (see *Figure 5.1*). These HR responses at absolute workloads are consistent with previous findings from RPE research that used unadjusted workloads (Robinson & Haymes, 1990), and consistent with researchers that reported similar HRs between sea level and altitude conditions at workloads adjusted according to percentage of VO_2max (Horstman, 1979; Maresh et al., 1988). The HR responses at absolute workloads are also similar to the results from a recent study of cross-country skiers during graded exercise performed in the same simulated altitude conditions (Hahn et al., 2001). Although HR is expected to increase during acute high altitude exposure, the moderate altitude condition used in this study (and the studies by Hahn et al. and Maresh et al.) might not have resulted in sufficient impairment of oxygen transport to meaningfully alter cardiac responses. HRs may increase at altitude to compensate for impaired oxygen delivery to working muscles caused by a reduction in the pressure gradient between alveolar and pulmonary capillaries. These alterations result in an approximate reduction of 3% in VO_2max for every 300 m of altitude above 1500 m (Armstrong, 2000). With the altitude test in this study being performed at 1800 m, the potentially small reduction in oxygen transport might not have been sufficient for meaningful increases in HR to occur.

There was little difference in La responses between conditions. Although there was a trend for lower La concentrations at altitude as workloads increased, the greater variability in La at higher workloads indicates little practical difference. Similar La responses at low workloads is expected and was found in recent research using the same treadmill protocol and the same simulated altitude conditions (Hahn et al., 2001). Similar to this study, Hahn et al. also found increases in the mean difference of La concentrations between conditions as workloads increased. Similar La concentrations at workloads relative to the AT and 90% of maximal work time is consistent with previous research that reported similar La responses between altitude and sea level tests at workloads adjusted according to VO_2max (Bouisou et al., 1986; Escourrou et al., 1984). Greater La responses at absolute workloads during exercise at altitude, particularly above the AT (see *Figure 5.2*), is also consistent with previous findings (Sutton, 1977).

Altitude had a large overall effect on the HR-RPE relationship, with generally higher RPEs being recorded for a given HR during tests performed at altitude compared to sea level. Although there were only small differences in variables between conditions, the divergent physiological and perceptual responses contribute to this large effect. The effect is also influenced by the large difference in the HR-RPE ratio found at the lowest exercise workload caused by lower HRs and greater RPE responses. As shown in *Figure 5.1* and Table 5.2, the differences in HR and RPE responses between altitude and sea level tests were mostly small beyond the first workload, and this pattern is also reflected in diminishing differences in HR-RPE ratios as workloads increased (see Table 5.3). It is possible that the stage one result occurred because this comparison was made at an absolute workload, whereas the later comparisons were made at workloads relative to La concentration and work time. At this unadjusted workload, hypoxia might have resulted in perceivable increases in respiratory mediators of RPE, such as V_E and respiratory exchange ratio (also found in altitude conditions at rest; Fulco & Cymerman, 1988) that might not have affected cardiac output at low workloads, but resulted in increased RPE. The finding in this study of higher RPEs for a given HR at altitude is similar to the results reported by Maresh et al. (1993) who tested moderate and low altitude natives at their resident altitude and at high altitude. The authors reported consistent decreases in HR at intensities above 75% of VO_2max for the low altitude group but not the moderate altitude group at high altitude. These responses were accompanied by similar RPEs between conditions for the low altitude group, but reductions in RPE for the moderate altitude group at altitude. Consistent with this study, these results suggest that participants not accustomed to altitude conditions exhibit higher RPEs for a given HR during exercise performed at high compared to low altitude.

The results from this study also showed that workload had a large and significant effect on the HR-RPE relationship. As workloads increased the HR-RPE ratio decreased, suggesting that RPE grows at a greater rate in relation to HR as exercise time and workload increase (see Table 5.3). As shown in *Figure 5.1*, the relationship between HR and RPE for trained athletes during incremental ski-striding tests was not linear as suggested in the RPE literature. In this study, the expected ratio of 10 to 1 for HR and RPE is not attained until near maximum workloads. These results can be partly attributed to the low RPEs reported early during exercise tests so that perceptual responses were able to increase from a lower base compared to HR. This result might be attributed to the combination of upper and lower body muscle groups involved in the ski-striding protocol. Sargeant and Davies (1973) showed higher power outputs and HRs for a given RPE with increases in the muscle masses involved (i.e., one arm, two arm, one leg, two leg). Gamberale (1972) and Borg et al. (1987) also reported similar results. Variations in the rate of reduction of the HR-RPE ratio as workloads increased (caused by the higher HR-RPE ratio found at stage 1 during tests at sea level compared to altitude) also contributed to the large but nonsignificant interaction effect.

Altitude had a large overall effect on the La-RPE relationship, with generally higher RPEs being recorded for a given La concentration during tests performed at altitude compared to sea level (see *Figure 5.2*). Table 5.2 shows that, at the lowest workload, the AT, and at 90% of maximum work time, RPEs were greater and La concentrations lower at altitude compared to sea level. These responses resulted in lower La-RPE ratios at these test points during altitude compared to sea level tests. As shown in *Figure 5.2*, at absolute workloads above the AT, La concentrations were greater during altitude tests. This result was most likely due to the AT occurring at a lower La concentration in altitude compared to sea level tests leading to an early increase in La accumulation during altitude tests.

Greater La concentrations during the later stages of the treadmill tests (absolute workloads) at altitude were accompanied by higher RPE responses, so that for a given La concentration RPE was greater throughout altitude compared to sea level tests (see *Figure 5.2*).

Despite the large overall effect size of altitude on the La-RPE relationship, the differences in the mean La-RPE ratios presented in Table 5.3 were small. The large effect is likely due to the small variation in La-RPE ratios between altitude and sea level tests. Although it is difficult to determine what are meaningful differences for RPE relationships between altitude and sea level conditions, these results show that, for a given La concentration, RPE responses are slightly greater during altitude testing. The small variation in mean La-RPE ratios and the large overall effect being nonsignificant limits the generalisability and reliability of these findings. These results should be examined using more participants and a larger difference in altitude between conditions. It is difficult to compare these results with those from previous research where reported results do not allow for an exploration of the *relationship* between RPE and physiological parameters during exercise. For example, Young et al. (1982) reported nonsignificant reductions in La at altitude at 85% of VO_2max (similar to this study), but reported differentiated RPE responses that were averaged over minute-5, 15, and 25 (also nonsignificant reductions). Similarly, Robinson and Haymes (1990) reported La concentrations at minute-45, 90, and 120, but reported RPE responses averaged over the whole exercise bout. These results cannot explicitly describe the *relationship* between La and RPE because responses were not reported at comparable workloads or time points. Other researchers have not measured La concentrations (Horstman et al., 1979; Maresh et al., 1988) or investigated low and moderate altitude acclimatised participants (Maresh et al., 1993). Overall, the mean differences in La, RPE, and La-RPE ratios reported in Tables 5.2 and 5.3 suggest that the altitude conditions in this study may not have provided sufficient impairment to exercise capacity to make meaningful conclusions about the effect of altitude on the La-RPE relationship in elite athletes.

The results from this study also suggest that workload had a large effect on the La-RPE relationship. Consistent with Study 1 and the moderate temperature condition in Study 2, the La-RPE ratio increased with increases in workloads. These results indicate that La increased at a greater rate than RPE as workloads increased. As discussed in Study 1, this result is not surprising given the greater growth exponent for La and workload compared to RPE and workload. Some variation in the growth in La-RPE ratios between conditions contributes to the moderate interaction effect. The mean La-RPE ratios presented in Table 5.3, however, suggest somewhat consistent rates of growth for this ratio.

Conclusion

Overall, the results from this study show that acute exposure to moderate altitude conditions had some affect on HR-RPE and La-RPE relationships. *Figures 5.1* and *5.2*, however, suggest that the altitude condition did not result in substantial overall effects between conditions. These results might be attributed to the moderate simulated altitude condition that may not have provided sufficient impairment of respiratory-metabolic systems to demonstrate more meaningful differences. The results from this study are somewhat novel in that they describe the *relationship* between RPE and physiological parameters during exercise tests in simulated altitude and sea level conditions. In addition, this is the first study to use elite athletes. The limitations of this study include not adjusting workloads at altitude according to reductions in VO_2max, not measuring ventilatory responses, and using moderate rather than high altitude conditions. Future researchers might wish to consider examining RPE relationships during exercise at comparable workloads adjusted according to reductions in VO_2max using acute *high* altitude conditions.

CHAPTER 6

A COMPARISON OF HEART RATE-RPE AND LACTATE-RPE RELATIONSHIPS IN ELITE ATHLETES TRAINED IN UPPER AND LOWER BODY SPORTS

Method

Participants

Members of the Australian Road Cycling Team (males = 5, females = 6) and the Australian Kayaking Team (males = 5, females = 6) participated in this study. Cyclists were aged between 19 and 26, kayakers between 20 and 30, and all participants competed internationally.

Measurement

For a description of HR, La, and RPE measures used in this study see the *Measurement* section of Chapter 3.

Procedure

Each participant completed one protocol-specific GXT during pre-competition camps. The kayak GXT test was performed on a modified rowing ergometer (Concept IIc Rowing Ergometer). The protocol started at 50 W for women and either 100 W ($n = 2$) or 50 W ($n = 3$) for men, depending on the weight of the athlete. The GXT consisted of five four-minute stages, with resistance increased 50 W for each of the first four stages followed by a final supramaximal stage in which participants were asked to work at maximal effort. The cycle GXT test was performed using a Lobe Excaliber electromagnetically braked bicycle (Lobe BV Groningen, The Netherlands). The protocol started at 100 W with the resistance increasing 50 W every five minutes until voluntary exhaustion. During the last 10 seconds of each work stage cyclists and kayakers were shown the RPE scale and asked verbally to rate their overall exertion. HR was monitored throughout the kayak and cycle GXTs and recorded immediately upon completion of each test stage. At the completion of each work stage a capillary blood sample taken from the ear lobe using the capillary puncture method.

Data Analysis

The variables of HR, La, and power output were plotted against RPE during upper and lower body exercise over each stage of the GXTs. To further examine the relationships between RPE and HR, and RPE and La, ratios between HR and RPE and La and RPE were compared between kayak and cycle GXTs. HR-RPE and La-RPE ratios were calculated for each participant following stage 1, at the AT, and upon completion of GXTs. Mixed design 2 (group) x 3 (time) ANOVAs were used to assess group (kayak vs. cycle) differences for RPE ratios at stage 1, the AT, and at the completion of the final stage of the GXTs. Interactions and main effects for workload and group are reported in terms of significance tests ($p < .05$) and effect sizes (η^2). The magnitudes of difference (Cohen's *d*) for RPE ratios at stage 1, the AT, and at the completion of the final stage of the GXTs are also reported. For a justification of statistical analyses see Chapter 3.

The AT was calculated according to the modified D-max method. For a description of this calculation and the methods used to obtain D-max see Chapter 3.

Results

Table 6.1 presents the means and standard deviations for RPE, HR, and La across three workloads during kayak and cycle GXTs. *Figure 6.1* illustrates the relationship between RPE and HR during each GXT. For workloads at or below the AT, HRs were greater at a given RPE during kayak GXTs compared to cycle GXTs. Cycling produced greater maximum HRs and RPEs compared to kayaking, and participants demonstrated greater HRs for a given RPE at the highest workloads during cycling. *Figure 6.2* shows the relationship between RPE and La during kayak and cycle GXTs. For a given RPE, La concentrations were consistently greater during kayak compared to cycle GXTs, and kayak

GXTs produced greater maximal La responses. RPEs at the AT were similar between kayak and cycle GXTs, but HR and La responses were greater at the AT during kayak tests. *Figure 6.3* shows the relationship between RPE and power during kayak and cycle GXTs. For a given RPE, power was consistently greater during cycle compared to kayak GXTs.

Table 6.1

Means and Standard Deviations During RPE, HR, and La for Kayak and Cycle GXTs.

Stage	RPE				HR				La			
	Kayak		Cycle		Kayak		Cycle		Kayak		Cycle	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	9.64	1.21	8.91	1.87	135.91	15.54	119.00	21.53	2.97	0.97	1.46	0.57
AT	15.27	1.89	15.14	1.16	174.55	7.49	170.18	6.54	6.76	1.41	3.92	1.25
Max	17.91	2.07	19.36	0.92	184.64	5.66	191.09	8.37	18.17	3.40	12.53	3.03

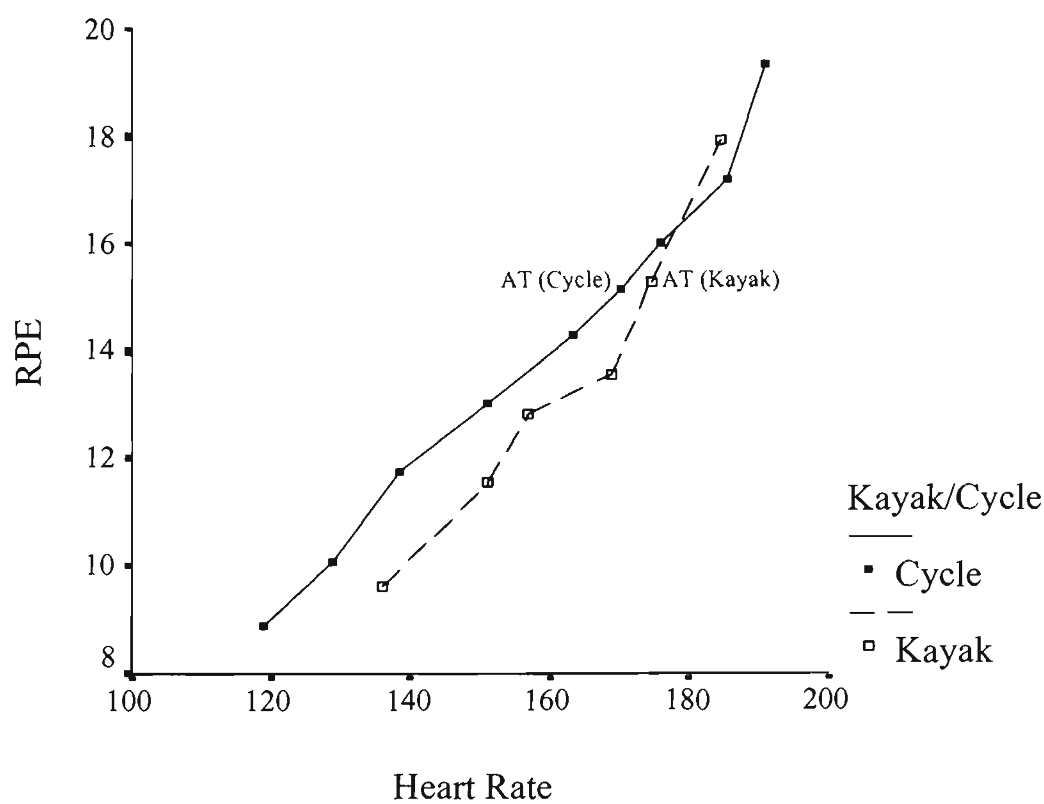

Figure 6.1. Variation in RPE with HR during kayak and cycle GXTs.

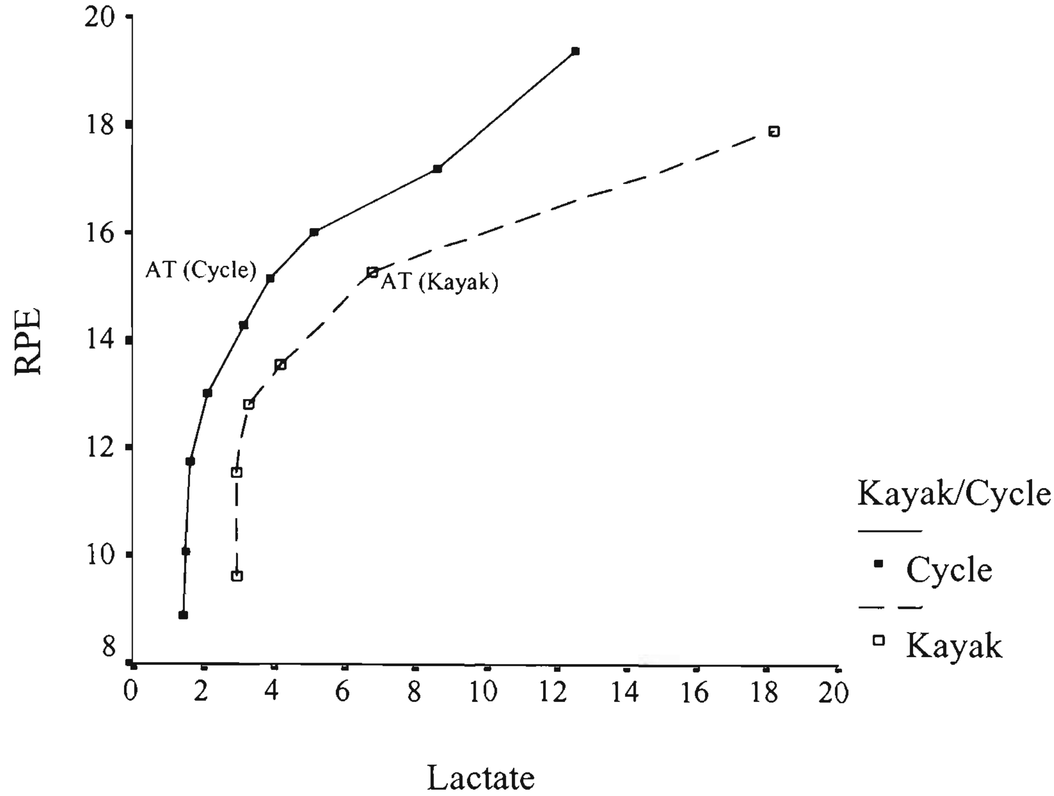

Figure 6.2. Variation in RPE with La during kayak and cycle GXTs.

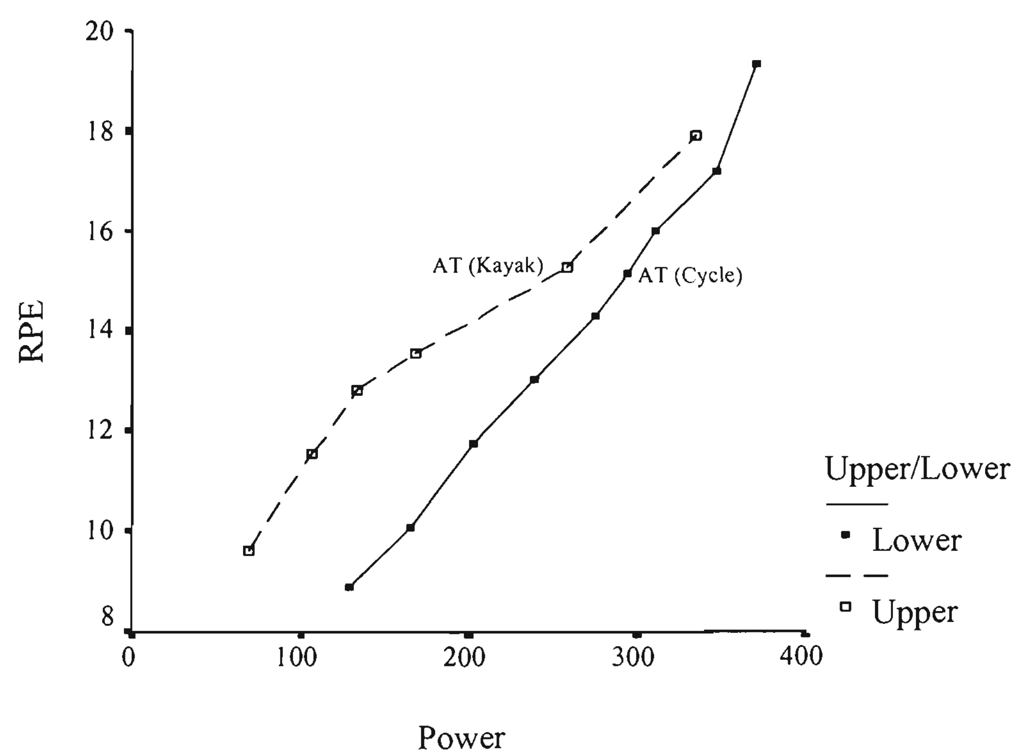

Figure 6.3. Variation in RPE with power during kayak and cycle GXTs.

Ratios between HR and RPE, and La and RPE were calculated to describe RPE relationships at different workloads between kayak and cycle GXTs. Table 6.2 presents the means and standard deviations for HR-RPE and La-RPE ratios at stage 1, the AT, and at maximal effort. Table 6.3 shows the results of the within-groups ANOVAs for kayaking and cycling HR-RPE and La-RPE ratios across the three workloads.

Table 6.2

Means and Standard Deviations for HR-RPE and La-RPE Ratios During Kayak and Cycle GXTs.

Time/ Stage	HR-RPE				La-RPE			
	Kayak		Cycle		Kayak		Cycle	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	14.31	2.35	13.59	2.19	0.31	0.10	0.17	0.06
AT	11.58	1.47	11.29	0.77	0.44	0.06	0.26	0.02
Maximal	10.45	1.36	9.88	0.54	1.02	0.17	0.65	0.14

Table 6.3

F-values, df, Significance Levels, and Effect Sizes Comparing RPE Ratios Between Kayak and Cycle GXTs.

Source	HR-RPE					La-RPE				
	F-value	*df*	*p*	η^2	Power	*F*-value	*df*	*p*	η^2	Power
Kayak/ Cycle	1.84	1.00	$p > .05$	.16	.20	93.42	1.00	$p < .05$	.90	1.00
Workload	36.16	1.21	$p < .05$	.78	1.00	333.40	1.65	$p < .05$	.97	1.00
Interaction	0.19	1.13	$p > .05$	.02	.13	6.24	1.60	$p < .05$	.38	.67

There was a significant main effect of workload on the HR-RPE relationship. This result represented a large effect ($\eta^2 = .78$), with HR at a given RPE decreasing with increases in workload (as indicated in Table 6.2). Results showed a large effect of kayak and cycle GXTs ($\eta^2 = .16$) and a small and probably meaningless nonsignificant interaction effect of kayak and cycle GXTs and workload ($\eta^2 = .02$) on the HR-RPE relationship. An examination of the magnitude of differences in the HR-RPE relationship between kayak and cycle GXTs at different workloads showed a small to medium difference at stage 1 ($d = 0.32$), a small difference at the AT ($d = 0.26$), and a medium to large difference at the highest workload ($d = 0.60$). These results represented a 13 percentile point shift in HR relative to RPE at stage 1, a 10 percentile point shift in HR relative to RPE at the AT, and a 23 percentile point shift in HR relative to RPE at the highest workload.

There was a significant main effect of workload on the La-RPE relationship. This result represented an extremely large effect ($\eta^2 = .97$), with La at a given RPE increasing with increases in workload (as indicated in Table 6.2). Results showed a significant and extremely large effect of kayak and cycle GXTs ($\eta^2 = .90$) and a significant and large interaction effect of kayak and cycle GXTs and workload ($\eta^2 = .38$) on the La-RPE relationship. An examination of the magnitude of differences in the La-RPE relationship between kayak and cycle GXTs at different workloads showed extremely large differences at stage 1 ($d = 1.77$), the AT ($d = 2.32$), and at the highest workload ($d = 2.40$). These results represented a 46 percentile point shift in La relative to RPE at stage 1 and a 49 percentile point shift in La relative to RPE at the AT and at the highest workload.

Discussion

The results from this study suggest that HR-RPE and La-RPE relationships are altered depending on whether exercise was predominantly upper or lower body. Athletes exhibited lower RPEs for given HRs (with the exception of the highest workload) and La concentrations during cycle compared to kayak GXTs (see *Figures 6.1* and *6.2*). As shown in Table 6.2, these outcomes resulted in lower HR-RPE and La-RPE ratios during cycle compared to kayak GXTs at low workloads, the AT, and at maximum intensity. As shown in Table 6.3, the different modes of exercise had greater effects on the La-RPE than the HR-RPE relationship.

RPE responses were greater during kayak compared to cycle ergometer tests at low exercise intensities, despite research results suggesting that low exercise intensities are unlikely to provide sufficient stimulus to differentiate between perceptions of exertion across conditions. Greater RPE responses in this group may be the result of high initial testing workloads presented to elite kayakers. The smaller muscle mass used in upper body work, combined with the high initial workload, might accentuate sensations associated with muscular contraction that are hypothesised to dominate perceptions of exertion in the first 30 seconds of exercise (Cafarelli, 1977). Differences in RPE at stage 1 of kayak and cycle GXTs might also be expected when mean La responses for kayakers at this stage were more than double that of cyclists.

Differences in RPEs at the AT were negligible between groups. Comparable RPEs at the AT follows expected trends given the contention by some authors that La inflection points are important anchors for perceptions of exertion (DeMello et al., 1987; Hetzler et al., 1991) and that RPEs are similar when workloads are adjusted for modality specific exercise capacity (Hetzler et al., 1991; Pandolf et al., 1984). Because workloads were greater during cycle compared to kayak tests, RPEs were greater for a given power output during kayak GXTs (see *Figure 6.3*). These results are consistent with previous research findings that suggest RPEs are greater at absolute workloads during upper body compared to lower body exercise (Eston & Brodie, 1986; Pandolf et al., 1984; Pivarnik et al., 1988).

Although RPEs were lower at maximal workloads during kayak compared to cycle GXTs, the physiological and perceptual responses reported are unlikely to represent true maximal performance for kayakers. Anecdotal reports from routine laboratory testing and feedback from participants in this study suggest that maximal kayak performance is difficult to attain using the modified rowing ergometer used in this study (Concept IIc Rowing Ergometer). Whereas high performance kayaking relies on smooth, continuous transitions between left and right arm work, the modified rowing ergometer was described as "clunky" at high workloads. Participants in this study spoke of being frustrated during the final supramaximal stage of the GXT because they could not produce a smooth kayaking action and felt unable to attain maximal performance. This factor may have contributed to lower maximal RPEs during kayak ($M = 17.91$) compared to cycle ($M = 19.36$) GXTs, with maximal RPE responses falling between "very hard" and "extremely hard" for kayakers, compared to "extremely hard" and "maximal exertion" for cyclists. This factor may also have contributed to lower maximal HRs during kayak GXTs (see Table 6.1).

HRs were greater at most workloads during kayak compared to cycle GXTs, despite lower power outputs during kayaking. These results are consistent with previous research findings that have shown greater HRs at absolute power outputs during upper body compared to lower body exercise (Pimental et al., 1984; Sawka et al., 1982; Vokac et al., 1975). Slightly higher HRs at the AT during kayak exercise are also in agreement with findings that suggest smaller differences in HR between upper and lower body exercise at workloads adjusted for modality specific exercise capacity (Taguchi & Horvath, 1987; Vokac et al., 1975). Greater maximal HRs during cycle GXTs found in this study are consistent with previous research findings (Sawka, 1986). Some researchers suggest, however, that the maximal HRs of upper body trained athletes during arm crank ergometer tests are close to, or exceed their maximal cycle ergometer HRs (Cerretelli et al., 1979; Seals & Mullins, 1982; Vrijens et al., 1975). It is possible that the problems associated with achieving maximal performance on the kayak ergometer also contributed to lower maximal HRs.

As shown in Table 6.1, athletes exhibited large increases in La concentrations during kayak compared to cycle GXTs. These differences are consistent with previous research findings that suggest that upper body exercise produces greater La concentrations at a given power output compared to lower body exercise (Pimental et al., 1984; Sawka, et al., 1982). As shown in *Figure 6.3*, the AT during kayak GXTs occurred at lower power outputs compared to cycle GXTs. This result is consistent with previous research findings that showed the AT occurs at a lower power output during upper compared to lower body exercise (Davis et al., 1976; Reybrouck et al., 1975). Greater maximal La concentrations during upper body exercise reported in this study, however, are not consistent with previous findings (Bergh et al., 1976; Sawka, et al., 1982). The results obtained in this study might be related to the highly trained state of participants. Training can increase maximal La concentrations in already trained athletes (Bourdon, 1999; Fukuba et al., 1999), and the factors limiting maximal La responses during upper body exercise (e.g., smaller muscle mass) might be mitigated by high intensity training.

Exercise mode had a large overall effect on the HR-RPE relationship. RPEs and HRs were greater during kayak compared to cycle GXTs at submaximal workloads, whereas at maximal workloads RPEs and HRs were lower during kayak tests (for reasons discussed earlier). The magnitudes of difference in HR and RPE from cycle to kayak GXTs resulted in greater HR-RPE ratios during kayak tests at all workloads (see Table 6.2), such that for a given HR, RPEs were lower during kayak compared to cycle GXTs for most of the ergometer tests (see *Figure 6.1*). As with some results in the previous studies, this large effect was not statistically significant. This result is suggestive of a Type II error. To assess the reliability of this finding, however, further, more powerful, studies need to be conducted to determine the reliability of this finding. This result is not supported by previous research results that showed higher RPEs at certain HRs during upper compared to lower body activities (Borg et al., 1987; Gamberale, 1972; Sargeant & Davies, 1973). The finding of lower RPEs for a given HR during kayak work is particularly interesting because La concentrations were greater during kayak tests (and greater for a given RPE, which is consistent with previous findings). Lower RPEs for a given HR in this study might be indicative of elite kayakers who are accustomed to high intensity upper body work on kayak ergometers. As with most research investigating the physiological and perceptual characteristics of upper body work, Borg et al. (1987) and Sargeant and Davies (1973) had participants perform upper body work using arm crank ergometers. It is possible that participants unaccustomed to isolated arm exercise using arm crank ergometers might perceive this work as particularly strenuous in relation to HR due to the novelty of the task and the technical inefficiencies associated with arm crank work. Researchers have demonstrated lower net efficiency indices (ratio of work to aerobic metabolic input) for arm crank compared to cycle exercise (Bergh et al., 1976; Davies & Sargeant, 1974; Toner et al., 1983). Technically efficient actions, likely to characterise participants in this study and indicative of high performance athletes, might increase the net efficiency index for upper body work. This potential increase in net efficiency means that upper body trained athletes could increase the work they perform for a given VO_2. Such adaptations might potentially result in increases in HR without equivalent alterations in mediators of exertion, such as V_E, and without resultant increases in RPE. Such differences in biomechanical efficiency, combined with elite athletes being accustomed to high intensity upper body work, might have resulted in lower RPEs for a given HR not found in research that used untrained participants on novel apparatus. This contention is supported by the findings of Boutcher et al. (1989), who reported reductions in RPE at the LT following cycle and run training, but only when testing used training-specific ergometers. Small increases in RPE at the LT were reported when testing was conducted on ergometers not matched to the modes of training. The familiarity of elite athletes with high intensity training might also have had an effect on the mediating role of La on RPE and resulted in alterations to the expected HR-RPE relationship during upper and lower body exercise. This issue will be elaborated on when the La-RPE relationship is discussed later in this section. Another factor is that this study involved a between-groups experimental design, whereas previous researchers used within-groups repeated measures designs. Possible differences in participant characteristics between groups might have contributed to the HR-RPE results in this study.

At the completion of the final stage of the GXTs kayakers had higher RPEs for a given HR compared to cyclists (see *Figure 6.1*). This change in the relation between HR and RPE between kayak and cycle exercise may have resulted from the difficulties experienced by participants with the modified rowing ergometer at high workloads (discussed earlier). These results were also potentially mediated by differences in blood pressure responses between upper and lower body exercise. Upper body work includes notable contributions from the isometric contraction of torso stabilising muscles, such as the abdominals, and these contributions are likely to be greater as workloads increase. This additional exercise demand can increase physiological activation and arterial blood pressure. Pandolf et al. (1984) found that blood pressure made important contributions to RPE during upper body but not lower body exercise. It is possible that increased blood pressure during kayak compared to cycle exercise might have made contributions to the perception of exertion that resulted in higher RPEs for a given HR for kayak compared to cycle exercise at the highest workload.

Workload had a large and statistically significant effect on the HR-RPE relationship. As shown in Table 6.2, HR-RPE ratios decreased with increases in workload during both cycle and kayak GXTs. This result is consistent with the findings from Study

1, Study 2, and Study 3 of this thesis and suggest that RPE grows at a greater rate in relation to HR as exercise workloads increase. As discussed earlier in this thesis, these results can be attributed to low RPE responses found early during exercise tests, and questions the contention that the HR-RPE ratio should approximate 10-1. This result is consistent for elite athletes during upper and lower body exercise, and, from the results of the earlier studies in this thesis, is also independent of state of training, altitude or sea level testing, and ambient temperatures. The small and nonsignificant interaction effect also suggests that the rate of reduction in HR-RPE ratios with increases in workload are similar for kayak and cycle GXTs.

Exercise mode had a large overall effect on the La-RPE relationship. Slightly greater submaximal RPE responses were accompanied by large increases in La concentrations during kayak compared to cycle GXTs. These responses resulted in greater La-RPE ratios during kayak compared to cycle tests (see Table 6.2) so that La concentrations were greater for a given RPE during kayak GXTs (see *Figure 6.2*). The magnitude of difference in La-RPE ratios between tests were extremely large throughout but tended to increase with increases in workload. The finding of greater La concentrations for a given RPE during kayak compared to cycle exercise is consistent with the few studies to explicitly examine the relationship between La and RPE between upper and lower body work. The La-RPE results from this study are comparable to those from Borg et al. (1987) who reported higher La concentrations at comparable perceptual ratings (both RPE and CR-10) during graded arm compared to leg work. Similarly, Gamberale (1972) found greater La responses at a given RPE during upper body (lifting weights) compared to graded cycle exercise and pushing weights in a wheelbarrow. Both these studies also reported lower HRs for a given RPE during upper body work, leading the authors to suggest that local factors might play a more important role than central factors in the perception of effort during upper body exercise. This conclusion might be less applicable to elite upper body trained athletes who are accustomed to high intensity upper body exercise, and for whom La accumulation might not limit exercise capacity to the extent it does in untrained individuals. As stated earlier, La accumulation is more rapid during submaximal upper body exercise, but research findings also suggest that La concentrations after maximal effort are lower for upper body compared to lower body exercise (Sawka et al., 1982). The results from this study, however, showed that maximal La concentrations were extremely high during kayak GXTs ($M = 18.17$) and were approximately 50% greater than cycle GXTs. Despite these La responses, RPEs at maximal effort were lower during kayak GXTs. The problems associated with the modified rowing ergometer, however, may have contributed to this perceptual response. It is possible that at workloads below the AT, La might provide less input into the effort sense during upper body exercise for trained compared to untrained participants. The possibility of La playing a less important role in mediating RPE during upper body exercise in elite athletes might help explain the different HR-RPE responses reported earlier. With La providing less input to the effort sense at a given workload in this study, lower RPEs for a given HR during kayak compared to cycle exercise (found at intensities below the AT in this study) might be expected.

Although the AT occurred at a greater power output during cycle GXTs and occurred at a higher La concentration during kayak GXTs, the mean RPE responses at the AT between the two test protocols were similar (see Table 6.1). Similar RPEs at the AT is consistent with Studies 1 and 3 of this thesis. In agreement with contentions in the RPE literature (Haskvitz et al., 1992; Hetzler et al., 1991; Seip et al., 1991), these results suggest that the AT might be an important anchor-point for RPE.

Workload had a large and significant effect on the La-RPE relationship, with La-RPE ratios increasing with increases in workload during both kayak and cycle GXTs.

These results suggest that La increases at a greater rate than RPE during incremental upper and lower body exercise in elite athletes. This result is consistent with theoretical expectations and the relative growth exponents of La and RPE with workload (discussed in Study 1) and is consistent with the results from Study 1, the moderate temperature condition in Study 2, and Study 3. There was also a large and significant interaction effect for the La-RPE relationship between kayak and cycle GXTs. As shown in Table 6.2, although the La-RPE ratio is greater throughout kayak GXTs, the rate of increase in this ratio is greater during cycle GXTs. This greater rate of increase for cycle GXTs is likely the result of the lower base from which the cycle GXT La-RPE ratios begin.

Conclusion

The results from this study show that elite kayakers had lower RPEs for a given HR compared to elite cyclists during GXTs. This result is not consistent with previous findings, but might be indicative of elite athletes accustomed to high intensity exercise isolated to specific upper-body muscle groups. In agreement with previous research findings, this study has shown that RPEs were lower for a given La concentration during kayak GXTs. These results, combined with extremely high maximal La concentrations for elite kayakers, suggests that La might play a less important role in mediating perceptions of exertion for upper body trained athletes compared to untrained individuals.

CHAPTER 7

GENERAL DISCUSSION AND CONCLUSIONS

Introduction

The main aim of this thesis was to describe the relationships between RPE and HR, and RPE and La in elite athletes during exercise testing across a variety of conditions. Comparing these results with previous research findings builds a picture of RPE relationships in highly trained individuals and identifies how and why these relationships might differ from those described for untrained or sub-elite participants. This general discussion will outline the characteristics of the HR-RPE and La-RPE relationships in elite athletes and elaborate on the implication of these results for exercise testing and future research. Concluding remarks follow this discussion.

Characteristics of RPE Relationships in Elite Athletes

Few researchers have investigated the relationship between RPE and physiological variables in highly trained elite athletes. Such investigations have become more common in recent years (e.g., Foster et al., 1999; Garcin et al., 2001; Hahn et al., 2001; Martin & Andersen, 2000) as the measurement of perceived exertion becomes more routine in monitoring athletes during training. To use RPE effectively in this context, it is important that researchers and practitioners are aware of the characteristics of RPE responses from elite athletes in conditions common during testing, training, and competition.

The results from this thesis show negligible differences in RPE responses from elite athletes at low intensities during graded swim tests performed in IS and OS training. The results from GXTs reported in Study 3 and 4, and the 30TTs in Study 2, however, show differences in RPE responses at low workloads. These responses might be attributed to the unadjusted workloads presented between altitude and sea level conditions in Study 3 and the high workloads presented to elite kayakers that resulted in early elevations in La and HR in Study 4. Higher RPEs early during 30TTs performed in hot ambient temperatures might be the result of the high target workloads presented to athletes combined with the sensations provided by high temperatures. Although similar perceptual responses across conditions are expected at low workloads and during the early stages of GXTs (Noble & Robertson, 1996), the relatively high initial workloads presented to elite athletes during exercise testing might result in altered perceptual responses across conditions early during exercise testing.

Similar RPEs at the AT within each study at least tentatively suggests La as an important perceptual cue for exertion in elite athletes. The variation in RPE responses at the AT between studies, however, suggests otherwise. As discussed in the review of literature, RPE is unlikely to be mediated by any single physiological paramenter. Variations in other potential mediators of RPE that are related to the demand characteristics of the different modes of exercise might explain these differences. In addition, the performance capabilities of participants between studies might also contribute to differences in RPE responses at the AT. RPEs at the AT for cross-country skiers (13.83 and 13.50) were less than for swimmers (16.17 and 16.67), cyclists (15.14), and kayakers (15.27). Lower RPEs at the AT for skiers may be because this group was not as elite as the athletes in the other studies (none of the members of the Australian team were ranked in the top 50 in the world for their event). The competitive standard of cross-country skiers might be indicative of lower states of training for these athletes compared to participants in the other studies, with La transition thresholds occurring lower on the perceptual range in this group.

Another possible explanation for these results is the combination of upper and lower body muscle groups involved in cross-country skiing. The results from some investigations suggest that increases in the muscle mass involved in exercise results in lower RPE responses for a given HR and power output (Borg et al., 1987; Gamberale, 1972; Sargeant & Davies, 1973). The high RPE responses at the AT for swimmers, however, is not consistent with this hypothesis. It is not clear why swimmers reported higher RPEs at the AT compared to other athletes. It is possible that factors related to breathing regulation and increased sensations associated with respiratory demand might have contributed to this result. Higher RPEs at the AT for swimmers agree with the suggestion of Noble et al. (1986) that central signals may dominate overall perceptions of exertion during swimming, when forced breathing patterns are necessary. Again, this contention would support RPE being mediated by a gestalt of physiological mediators rather than one single mediator such as La.

RPE responses at maximal effort differed between studies. Results at high exercise intensities from cross-country skiers were reported at 90% of maximal work time, and mean perceptual responses reflect this submaximal workload (18.16 and 18.07). As discussed earlier, maximal kayak responses were limited by problems with the modified kayak ergometer. Cyclists in Studies 2 and 4 responded with the highest mean perceptual ratings (between 19.04 and 19.36), which were greater than those from swimmers in Study 1 (18.67 and 18.75). It is possible that maximal perceptual ratings from elite athletes might be closer to true maximal responses when specialist ergometers are used in controlled laboratory conditions. Such conditions allow athletes to concentrate fully on achieving maximal power outputs without distraction from environmental and psychological factors present during field conditions (e.g., athletes swimming in adjacent lanes, the presence of other support staff). This suggestion is consistent with the findings of Ceci and Hassmén (1991) and Thompson and West (1998) who found higher RPEs for given physiological and performance outcomes during laboratory compared to field tests. Although different experimental designs make direct comparisons difficult, these results suggest that individuals might not process sensory information relating to physical exertion in the same way in laboratory and field testing conditions. In relation to this assertion, another factor that might affect the attainment of maximal exertion by elite athletes is the motivational climate during testing. Whereas cyclists in laboratory testing typically have others present providing verbal encouragement, such direct motivational factors are not available to swimmers completing laps in a pool. These results support the contribution of psychological factors in influencing perceived exertion responses.

The relationships between HR and RPE were affected by some of the experimental conditions presented in this thesis. The effects of some of these conditions on HR-RPE were not consistent with previous research findings from untrained or non-elite participants, and suggest that there are a number of characteristics of the HR-RPE relationship in elite performers that need further exploration. Further research is also recommended on the grounds that most of the changes in HR-RPE relationships showed large overall effects but were statistically nonsignificant. Although this is suggestive a Type II error, this is not necessarily the case. The reliability of the findings of alterations in HR-RPE relationships in elite athletes needs to be established using more participants and more power to detect differences between groups and conditions.

First, the results from Study 1 show that elite swimmers had greater HRs (and swam faster) for a given RPE during IS compared to OS training. These results make practical sense by suggesting that, through improvements in training state, elite athletes can sustain higher levels of physiological activation and performance without greater perceptions of physiological demand.

Second, the responses from Study 2 show that high ambient temperatures result in greater RPEs for a given HR for elite athletes during the second half of 30TTs. As discussed earlier, these results are not consistent with previous findings but might be applicable to the high exercise intensities performed by elite athletes. Third, slightly higher HRs were found for a given RPE in highly trained cross-country skiers during tests performed in simulated moderate altitude compared to sea level conditions. It is questionable, however, whether the altitude condition presented in this study was sufficient to produce meaningful effects on RPE relationships, and the small mean differences for perceptual and physiological responses reflect this assertion.

Finally, lower RPEs were found for a given HR during kayak compared cycle GXTs. These responses are inconsistent with previous research findings and might be the result of the technically efficient actions of athletes, the familiarity of the participants with the testing equipment, and that participants were accustomed to high intensity upper body exercise. Together, these results suggest that the characteristics of highly trained athletes might affect HR-RPE relationships although the reliability of such a conclusion needs to be tested by further research.

In addition to the effect of experimental conditions, workload or exercise duration had large effects on HR-RPE relationships. In all conditions presented in this thesis, HR-RPE ratios decreased with increases in workload and exercise duration. The magnitude of some of the HR-RPE ratios reported here are consitent with Borg's (1970, 1982) estimation that HRs should be fairly close to 10 times the corresponding RPE value at moderate or greater exercise intensities. As expected, this HR-RPE approximation was not evident at low exercise intensities across the studies. The findings of increases in HR without corresponding increases in RPE might also be expected considering elite athletes are accustomed to high intensity training. Low workloads in comparison to athletes' exercise capacity will result in increases in HR but may be considered extremely light by athletes accustomed to high exercise workloads. Results from this thesis show that, from a low base, perceptual responses increased at a greater rate than HR, so that by the AT or maximal exertion athletes exhibited HR-RPE ratios that more closely approximated Borg's original estimation. This result is consistent with a recent study by Martin and Andersen (2000), who reported HR-RPE ratios of between 11.94 and 14.34 at a HR of 150 bpm for elite athletes during high intensity training and taper.

The experimental conditions presented in this thesis also affected the relationship between La and RPE. The results from Study 1 showed that, during IS training, lower RPE responses were accompanied by greater La concentrations when compared to OS training. This effect was contingent upon the workloads presented, with the magnitude of increase in La concentrations for a given RPE during IS training increasing at higher workloads. These results are inconsistent with most previous research findings, but agree with the findings from recent research that also reported perceptual and physiological responses from elite performers (Martin et al., 1999). Similar to the HR-RPE results, these responses show that athletes were able to sustain higher levels of physiological demand during IS compared to OS training without concomitant increases in perceived exertion. The results from Study 2 show that high ambient temperatures presented during self-paced exercise tests with elite cyclists disturbs the relationship between La and RPE. Although RPE responses rose steadily with exercise duration in the hot condition, La responses decreased (in conjunction with reduced power outputs) during the middle stages of the exercise test. These results suggest that, in hot ambient temperatures, perceptions of exertion were the primary mediator of exercise intensity for elite cyclists during a 30TT. These results also indicate that high ambient temperatures contribute to perceptions of exertion, independent of La and workload, for elite athletes. The results also suggest that RPE is not only mediated by the combination of several physiological cues but also by non-specific mediators such as ambient temperature. This result is not consistent with previous research findings and might be attributable to the high exercise intensities performed by elite athletes during testing and the effect of high workloads on core and skin temperature. The results from Study 3 show that, during GXTs performed in a moderate altitude condition, RPE responses were slightly greater for a given La concentration compared to tests conducted at sea level. Differences in the La-RPE relationship between conditions, however, were small, and it is questionable whether the altitude condition presented in this study was sufficient to produce meaningful differences in RPE relationships. The results from Study 4 show that the relationship between La and RPE in elite athletes differed depending on the type of exercise performed (upper or lower body). Greater La concentrations were reported for a given RPE during kayak compared to cycle GXTs and differences became greater as workloads increased. This result is consistent with previous research findings, although very high maximal La concentrations for elite kayakers, combined with lower RPEs for a given HR, raises the possibility that La plays a less important role in mediating RPE during upper body work in elite upper body trained athletes compared to untrained or sub-elite participants.

The relationship between La and RPE was also affected by workload or accumulated work. With the exception of the hot ambient temperature condition presented in Study 2, La-RPE ratios were greater when workloads or accumulated work increased. These results suggest that, as exercise tests progressed, La increased at a greater rate compared to RPE. These responses are in agreement with previous research findings (Borg et al., 1987) and the most recent text on perceived exertion (Borg, 1998) that report growth exponents for La and RPE with workload of 2.5 and 1.0 respectively. Differences in La-RPE ratios were greatest between the AT and high workloads. These results are indicative of the rapid increase in La that occurred beyond the AT, whereas RPE continued to increase linearly with workload. The only condition where the effect of accumulated work on the La-RPE relationship differed was in hot ambient temperatures during 30TTs. In this condition, power outputs performed by cyclists were adjusted down during the middle part the 30TTs so that participants could complete the test with the highest average power output possible. These results suggest that, in hot ambient temperatures, RPE responses from elite cyclists during a self-paced 30TT are more related to accumulated exercise time than to La accumulation or power outputs at a given point in time. In addition, these results suggest that, during self-paced exercise protocols performed in hot conditions, elite athletes will pace themselves according their perceptions of exertion, independent of factors thought to mediate RPE, such as La and workload.

Overall, the results from this thesis suggest that the relationship of RPE with HR and La in elite athletes is altered by some of the conditions which athletes are exposed to during exercise testing, training, and competition. The results from this thesis suggest that the standards currently presented in the RPE literature might not be applicable to elite, highly trained athletes. If RPE is used to monitor the responses of elite athletes during exercise testing, further research needs to be conducted to establish the characteristics of RPE relationships in highly trained participants and the reliability of some of the observations made in this thesis.

Implications for Using RPE During Exercise Testing with Elite Athletes

The results presented in this thesis raise a number of issues around the use of RPE during exercise testing in elite or highly trained athletes. The results from Study 1 show that HR-RPE and La-RPE relationships were altered in elite athletes between IS and OS training periods, suggesting the potential for monitoring training adaptations by relating RPE responses to physiological parameters during exercise testing. *Figures 3.1* and *3.2* show that RPEs were associated with greater HRs and Las when athletes' state of training improved. This result makes practical sense by suggesting that fitter athletes can sustain higher rates of physiological demand without perceiving related workloads as any more strenuous. As demonstrated by recent research findings (Martin et al., 2000), alterations in the HR-RPE relationship can be used to monitor training adaptations in elite athletes and potentially predict performance outcomes. In addition, HR-RPE and La-RPE ratios have been used to monitor fatigue during training and, thus, potentially avoid overtraining (Garcin et al., 2002; Martin et al.; Snyder et al., 1993).

The findings reported from Study 2 suggest that high ambient temperatures contribute to greater perceptions of exertion for elite athletes. Although increased HRs found in the hot condition were expected, the additional perceptual response resulted in greater RPEs for a given HR during the later stages of 30TTs performed in hot temperatures. This result is inconsistent with previous research findings with untrained or sub-elite participants. As discussed earlier in this thesis, the high workloads performed by elite athletes might result in a threshold increase in core body temperature that stimulates suggested mediators of RPE such as skin blood flow and sweat rate. The La-RPE results from Study 2 showed that, during a self-paced exercise protocol in hot conditions, RPE incrementally increased with test duration despite reductions in power output and La concentrations during the middle stages of the test. In practice, these results might be used to monitor the ability of athletes to effectively pace their performance during self-paced exercise in hot conditions. For example, rapid increases in RPE early during tests might indicate unsustainable exercise intensities that will result in the athletes not achieving their performance goal of attaining the highest average power output over the duration of the test.

The RPE relationships presented in Study 3 show only small differences between responses during tests in moderate altitude and sea level conditions. These results suggest that researchers and exercise practitioners need to consider the elevation at which testing is conducted when examining the effects of altitude on the relationship between perceptual and physiological parameters. Researchers should take into account expected reductions in exercise capacity of only 3% for every 300m of elevation above 1500 m of altitude (Armstrong, 2000). High, rather than moderate altitudes, might be required to produce meaningful differences in RPE relationships from sea level. Also of interest is that the cross-country skiers who participated in Study 3 responded with lower RPE responses at the AT compared to athletes in the other studies in this thesis. This result might be related to the lower competitive standard of the cross-country skiers or the characteristics (i.e., upper and lower body exercise) of the ski-striding protocol.

The results from Study 4 show that the relationship between RPE and physiological parameters for upper body trained elite athletes might not follow the findings from previous research that used untrained participants unfamiliar with exercise on arm ergometers. Whereas theoretical explanations suggest that the smaller muscle masses involved in upper body exercise should result in greater RPEs for a given HR, this relationship might not apply to athletes accustomed to high intensity upper body work on familiar test ergometers. In addition, the high maximal La concentrations of elite upper body trained athletes might lessen the mediating role of La on RPE responses. In this context, high maximal La-RPE ratios found in Study 4 would be expected.

Development of the RPE scale centred on a ratio between HR and RPE of approximately 10 to 1 for a healthy person aged between 30 and 50. Borg later stated that this relationship was potentially affected by factors, such as age, exercise type, environment, and anxiety (Borg, 1982). Although many research findings have not shown that workload affects the proposed HR-RPE ratio (e.g., Davies & Sargeant, 1979; Sjöberg et al., 1979; Toner & Drolet, 1986), others have reported low RPEs relative to heart rate at lesser workloads (e.g., Eston & Williams, 1986; Mihevic, Gliner, & Horvath, 1981). The findings from this thesis suggest that such a result might be particularly applicable to elite or highly trained athletes. Lower workloads presented early during GXTs will result in an increase in HR, but might not result in increases in perceptions of exertion for highly trained participants accustomed to performing at extremely high intensities.

The results from this thesis and recent research findings (Garcin et al., 2002; Martin et al., 2000; Snyder et al., 1993) suggest that the ratio between RPE and selected physiological variables might offer valuable information about the fitness of athletes and their ability to perform in competition. Some of the univariate results showed only small differences between conditions. When divergent perceptual and physiological responses are obtained (e.g., the reductions in RPE and increases in physiological activation found in Study 1 from OS to IS training), however, ratio calculations during exercise tests potentially provide a more sensitive indicator of adaptations to training compared to changes in single variables at a given power output. RPE ratio calculations could be particularly useful for monitoring elite athletes during training, where high performance capabilities limit the amount of variability in single parameters as a function of training. In addition, the use of ratios between perceptual and physiological variables across conditions might offer exercise scientists and athletes an indication of how individuals might perform in particular conditions.

Results from the four experimental conditions presented in this thesis should be taken together when considering the use RPE relationships during testing with elite athletes. Interactions between factors, such as test conditions, stage of the athletic season, current phase of training (e.g., overreaching), the competitive standard of the athletes, and the total muscle mass involved in exercise, should be considered when interpreting the physiological and perceptual responses from elite athletes during exercise testing.

Implications for Future Research

Much of the RPE research to date has investigated RPE and physiological responses separately across a range of power outputs. Rather than explicitly investigating the relationship between RPE and physiological parameters, this type of analysis describes the relationship between RPE and power and, for example, HR and power and expects the reader to join the dots. The capacity to explore the relationship between RPE and physiological parameters using this type of analysis is further hampered by the presentation of results in some journals that centre around graphical representations without reporting exact means and variations for a variable. In this case, readers are left to estimate the difference in responses between conditions for two variables and then approximate how the relationship between these variables change. More research is needed that explicitly analyses the *relationship* between RPE and physiological responses. Also, researchers should at least provide sufficient information for readers to determine these relationships for themselves. As discussed in the previous section, this recommendation might be particularly important when examining RPE relationships in elite athletes where the variability in single variables might be small.

Future research needs to investigate the stability of RPE responses at La transition thresholds between elite athletes trained in different sports, tested on different ergometers, competing at different competitive levels, and at different stages of training. Although differences in RPE responses at the AT within each study were small, there was some variation between studies. These differences might be related to the competitive standard of the athletes and the characteristics of the different sports. Researchers also should investigate multiple mediators of RPE at the La transition thresholds to determine if differences in RPE can be attributed to differences in other physiological responses such as

V_E. Researchers might wish to consider the mechanisms by which different sports and participant attributes affect RPE responses at La transition thresholds.

The study results presented in this thesis and recent research findings from elite athletes have reported HR-RPE and La-RPE relationships. Future research should investigate the relationship between RPE and respiratory variables, such as V_E or RR. Ventilatory variables have the potential to mediate perceptions of effort and the relationship between RPE and these variables might provide further information about the characteristics of RPE responses in elite athletes. Researchers should consider using relative percentages of VO_2max and ventilatory transition thresholds to compare RPE responses. Given the contention that RPE is determined by a gestalt of physiological determinants (Mihevic, 1981; Pandolf, 1983), and that physiological responses during exercise involve an integration of different systems, it is important that future RPE research looks at a variety of determinants to build a comprehensive picture of the perception of effort in elite athletes.

The effect of training period on RPE responses was investigated in this thesis using elite swimmers and has been examined with elite speed skaters (Foster et al., 1999). Other researchers have investigated RPE during short-term phases of training, such as responses to taper in elite cyclists (Martin et al., 2000) and overreaching with elite cyclists and runners (Garcin et al., 2002; Snyder et al., 1992). Future research should continue to examine RPE relationships during different stages of training to establish trends that could be used to monitor training adaptations in elite athletes. Such research should examine how the characteristics of different sports and testing ergometers might affect these relationships.

Study 2 in this thesis described the effect of high ambient temperatures on RPE relationships in elite cyclists during a self-paced time trial. This study produced some interesting results about how elite athletes pace themselves during a 30TT and how the relationship between La and RPE changes in hot conditions. The different ambient temperatures and the self-paced test protocol, however, resulted in athletes performing at different workloads between conditions. Future research should examine the effect of ambient temperature on RPE relationships in elite athletes during GXTs or steady-state protocols at comparable power outputs. RPE research with untrained participants has demonstrated temperature induced increases in La and HR without resultant increases in perceptions of exertion. Future research should consider whether the high workloads associated with elite athletic training might result in greater RPEs in hot ambient temperatures as discussed in chapter 4.

The equivocal results presented in Study 3 compared sea level responses with responses at a moderate simulated altitude. Future research should examine RPE relationships at high altitudes that sufficiently impede exercise capacity. Considering that this thesis demonstrated workload effects on RPE relationships in elite athletes, future research that examines the effect of altitude on RPE relationships should adjust workloads according to reductions in VO_2max at altitude. Without such adjustments, participants will be working at different workloads relative to condition-specific exercise capacities.

Concluding Remarks

The overall aim of this thesis was to examine RPE relationships in elite athletes in a variety of conditions and compare these results with those from previous research. The characteristics of elite athletic training (e.g., high exercise demands, training-induced fatigue, high exercise capacities) introduce factors that might affect relations between perceptual responses and physiological parameters. Most of the RPE research, however, is based on results from untrained or sub-elite performers. It is important that RPE relationships in elite athletes are explored further for perceived exertion to become a useful tool for monitoring the condition of athletes during training and in preparation for competition. The results from this thesis and some recent research suggest that RPE relationships can be used to monitor training adaptations and guard against overtraining in elite athletes. This thesis provides additional data about RPE relationships in elite athletes across a variety of conditions. This is the first time the relationship between perceptual and physiological responses has been explored across such a variety of conditions in elite athletic performers. Some of the results in this thesis need to be examined using different testing protocols and athletes from different sports. The results from this thesis provide the basis for future studies to develop a body of literature to describe comprehensively the characteristics of RPE relationships in elite athletes.

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APPENDIX

Acronyms/Abbreviations Used in This Thesis

Acronym/Abbreviation	Meaning
FT	Fast twitch
ST	Slow twitch
LT	Lactate threshold
AT	Anaerobic threshold
VCO_2	Carbon dioxide excretion
VO_2	Oxygen consumption
VO_2max	Test to determine maximal oxygen consumption
CR-10	Borg category ratio scale
RPE	Perceived exertion measured by the Borg RPE scale
La	Lactate
HR	Heart rate
RR	Respiratory ratio
CO_2	Carbon dioxide
O_2	Oxygen
N_2	Nitrogen
GXT	Graded exercise test
30TT	30-minute time trial
FBLC	Fixed blood lactate concentration
H^+	Hydrogen ion
CHO	Carbohydrate
FFA	Free fatty acid