

BIOFEEDBACK  
APPLICATIONS IN  
PERFORMANCE  
ENHANCEMENT

# BRAIN AND BODY IN SPORT AND EXERCISE

EDITED BY

BORIS BLUMENSTEIN  
MICHAEL BAR-ELI  
GERSHON TENENBAUM

# **Brain and Body in Sport and Exercise**

Biofeedback Applications  
in Performance Enhancement

*Edited by*

**Boris Blumenstein**

*Wingate Institute for Physical Education  
and Sport, Israel*

**Michael Bar-Eli**

*Ben-Gurion University of the Negev, Beer-Sheva;  
and Wingate Institute for Physical Education  
and Sport, Israel*

**Gershon Tenenbaum**

*Florida State University, USA*



JOHN WILEY & SONS, LTD

Copyright © 2002 by John Wiley & Sons, Ltd.,  
Baffins Lane, Chichester,  
West Sussex PO19 1UD. UK

National 01243 779777  
International (+44) 1243 779777

e-mail (for orders and customer service enquiries): [cs-books@wiley.co.uk](mailto:cs-books@wiley.co.uk)  
Visit our Home Page on: <http://www.wiley.co.uk> or <http://www.wiley.com>

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1P 0LP, UK, without the permission in writing of the publisher.

*Other Wiley Editorial Offices*

John Wiley & Sons, Inc., 605 Third Avenue,  
New York, NY 10158-0012, USA

WILEY-VCH Verlag GmbH, Pappelallee 3,  
D-69469 Weinheim, Germany

John Wiley & Sons Australia, Ltd., 33 Park Road, Milton,  
Queensland 4064, Australia

John Wiley & Sons (Asia) Pte, Ltd., 2 Clementi Loop #02-01,  
Jin Xing Distripark, Singapore 129809

John Wiley & Sons (Canada), Ltd., 22 Worcester Road,  
Rexdale, Ontario M9W 1L1, Canada

***British Library Cataloguing in Publication Data***

A catalogue record for this book is available from the British Library

ISBN 0-471-49906-4 (cased)

ISBN 0-471-49907-2 (paper)

Typeset in 10/12pt Times from the author's disks by TechBooks, New Delhi, India  
Printed and bound in Great Britain by Biddles Ltd., Guildford and King's Lynn  
This book is printed on acid-free paper responsibly manufactured from sustainable forestry,  
in which at least two trees are planted for each one used for paper production.

## CHAPTER 5

# Biofeedback in Exercise Psychology

Panteleimon Ekkekakis and Steven J. Petruzzello

### INTRODUCTION

Exercise psychology is concerned primarily with the psychological changes that accompany acute and chronic exercise and the psychological processes that underlie the participation in and adherence to exercise programs. Unlike sport psychology, the populations typically involved in exercise psychology research are nonathletic and the objective is not the enhancement of athletic performance, but rather the promotion of health and well-being.

Most of the studies on the use of biofeedback techniques in the context of exercise were conducted in the late 1970s and early 1980s (see earlier reviews by Petruzzello, Landers, & Salazar, 1991; Zaichkowsky & Fuchs, 1988). For reasons that we will examine shortly, the interest in biofeedback within exercise psychology has since been on the decline. This is unfortunate, however, because, as we will attempt to demonstrate, biofeedback techniques may provide effective solutions to some important problems encountered in health- and well-being-oriented exercise programs. In this chapter, we will (a) examine the reasons for the reduced interest in biofeedback within exercise psychology in recent years, (b) establish a rationale for the use of biofeedback in exercise settings, (c) review the research literature on the effectiveness of biofeedback for regulating exercise intensity, and (d) propose some future directions.

From a practical standpoint, the greatest challenge facing researchers in exercise psychology today is increasing the rates of public participation in and adherence to exercise programs. Evidence from a growing number of epidemiological and experimental studies shows that regular exercise is associated with a host of important health benefits [United States Department of Health and Human Services (USDHHS), 1996]. Yet the rates of public participation in exercise programs remain low and the rates of dropout remain high. Specifically, in the United States, the 1998–1999 progress review of the Healthy People 2000 program showed that only 23% of adults engage in

light-to-moderate physical activity five times per week and only 16% engage in light-to-moderate physical activity seven times per week (United States National Center for Health Statistics, 1999). Both figures have remained virtually unchanged since 1985 (22% and 16%, respectively) and both fall short of the targets for the year 2000 (30% for both categories). Furthermore, about half of the people who initiate an exercise program are likely to drop out within the first six months, while cognitive and behavioral interventions designed to increase the rates of participation and adherence typically meet with limited success (Dishman & Buckworth, 1996).

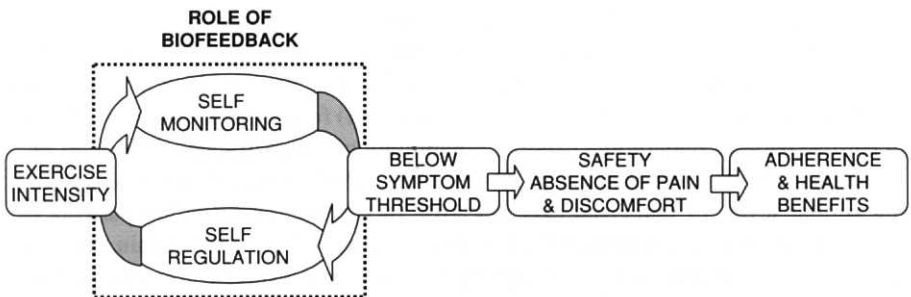
Traditionally, the problem of exercise involvement and adherence has been approached from a social-cognitive perspective (USDHHS, 1996). From this perspective, exercise participation is explained through such variables as attitudes, subjective norms, or self-perceptions. However, other perspectives may also help shed some light on this issue. As a case in point, research in general psychology has shown that the affect experienced in a situation is a good predictor of the amount of time people subsequently choose to spend in that situation (Emmons & Diener, 1986). In simple terms, in exercise, as in other domains, people are likely to do what makes them feel good and avoid what makes them feel bad. Why is this observation relevant to the issue of biofeedback? There is growing evidence that the intensity of exercise is closely associated with people's affective responses to the exercise. Specifically, it has been shown that increases in exercise intensity are linked to declines in affective valence (Acevedo, Rinehardt, & Kraemer, 1994; Hardy & Rejeski, 1989; Parfitt & Eston, 1995; Parfitt, Eston, & Connolly, 1996; Parfitt, Markland, & Holmes, 1994; see Ekkekakis & Petruzzello, 1999, for a review). Although a clear relationship between affective responses and exercise adherence remains to be established, it is noteworthy that studies have also shown an inverse relationship between exercise intensity and adherence (Epstein, Koeske, & Wing, 1984; Lee, Jensen, Oberman, Fletcher, Fletcher, & Raczynski, 1996; Sallis, Haskell, Fortmann, Vranizan, Taylor, & Solomon, 1986).

Consistent with these findings, recent physical activity recommendations have called for moderate-intensity activities. According to the National Institutes of Health Development Panel on Physical Activity and Cardiovascular Health (National Institutes of Health, 1996), such activities are recommended because they are "more likely to be continued than are high-intensity activities" (p. 243). Similarly, according to the newly issued Healthy People 2010 program, "each person should recognize that starting out slowly with an activity that is enjoyable and gradually increasing the frequency and duration of the activity is central to the adoption and maintenance of physical activity behavior" (USDHHS, 2000, p. 22-4). At the same time, however, as several authors have pointed out, starting out "too slow" may entail a substantial time commitment with negligible fitness or health benefits (Lee, Hsieh, & Paffenbarger, 1995; Morris, 1996; Winnett, 1998). Individuals who begin an exercise program typically have high expectations of fitness and health benefits, which, if not met, may lead to disappointment (Desharnais, Bouillon, & Godin, 1986) and, eventually, to disengagement from exercise.

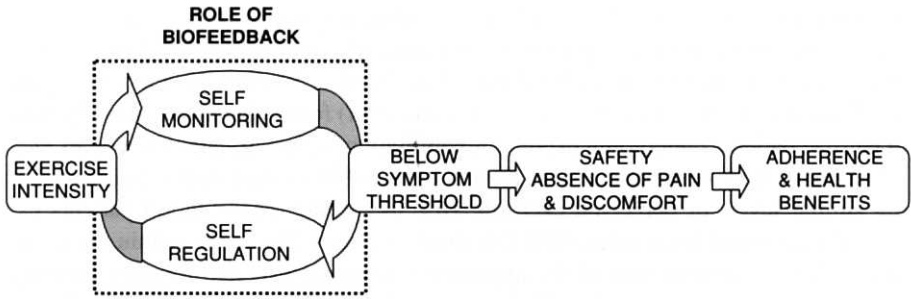
The problem is that individuals beginning an exercise program for the first time cannot be expected to know what constitutes a "slow" start or an appropriate progression.

Research has shown that most people are not intuitively (i.e., without training) capable of accurate self-monitoring and self-regulation of exercise intensity (Kollenbaum, 1994; Kollenbaum, Dahme, & Kirchner, 1996; Kosiek, Szymanski, Lox, Kelley, & MacFarlane, 1999). For example, Kollenbaum (1994) found that approximately 40% of cardiac patients undergoing exercise rehabilitation underestimated their heart rate, while about 10% overestimated it. Kosiek et al. (1999) found that, despite reporting similar levels of perceived exertion, 16% of cardiac rehabilitation patients exceeded their target heart rates, 67% fell short, and only 20% were within the target range. An underestimation of the appropriate range of exercise training intensity may result in overexertion, risk of injury or cardiovascular complications (Dishman, 1994), increases in the perceived aversiveness of exercise (Brewer, Manos, McDevitt, Cornelius, & Van Raalte, 2000), and, eventually, the discontinuation of the exercise program. On the other hand, an overestimation may deprive the exerciser of many of the potential benefits of the exercise program, thus possibly leading to frustration and drop-out.

For these reasons, it is critical that exercise be performed within a range of intensity that maximizes the health and fitness benefits (through the proper application of the training principles of overload and progression) without being experienced as aversive and without creating a risk for injury or cardiovascular problems. Biofeedback can be of great value in achieving these objectives. According to our conceptual model, in healthy populations (Figure 5.1), the role of biofeedback is to help exercisers improve their ability to self-monitor and self-regulate the intensity of their effort. By doing so, it is assumed that they will be able to regulate the level of perceived exertion and thus the valence of the affective responses that they experience. In turn, this is expected to contribute to an enhancement of the sense of enjoyment and satisfaction that the participants derive from the exercise experience. Ultimately, this should lead to improved adherence rates. In clinical populations (Figure 5.2) suffering from exercise-limiting conditions (e.g., exertion-induced angina, exertion-induced asthma, dyspnea due to



**Figure 5.1** Conceptual model for the role of biofeedback in exercise for healthy populations. By improving the self-monitoring and self-regulation of exercise intensity, biofeedback should allow exercisers to control the level of perceived exertion and affective valence that they experience. In turn, this should lead to more enjoyment and satisfaction and, ultimately, to improved exercise adherence rates.



**Figure 5.2** Conceptual model for the role of biofeedback in exercise for clinical populations with exercise-limiting conditions (e.g., exertion-induced angina, exertion-induced asthma, dyspnea due to chronic obstructive pulmonary disease, pain due to arterial claudication, etc.). By improving the self-monitoring and self-regulation of exercise intensity, biofeedback should allow patients to maintain a level of exercise intensity that is below the threshold that elicits unpleasant or dangerous symptoms. This should improve the safety and reduce the aversiveness of exercise, thus encouraging patients to remain physically active.

chronic obstructive pulmonary disease, pain due to arterial claudication, etc.), biofeedback may be an effective method of teaching patients to recognize some early warning signs or symptoms. By doing so, the patients may be able to maintain the level of exercise intensity below the threshold that elicits unpleasant or dangerous symptoms.

## WHY THE INATTENTION TO BIOFEEDBACK WITHIN EXERCISE PSYCHOLOGY?

The inattention toward biofeedback in exercise psychology is a reflection of the theoretical perspectives that have prevailed in this scientific field during the 30 or so years of its evolution. The perceptions of exertion and the affective responses that accompany exercise participation have been mainly examined from the perspective of cognitive and social-cognitive theories. The common theme that characterizes these approaches is that human experiences are formed in and, therefore, depend on the mind. The body is believed to provide the mind with raw sensory data but these data do not influence human experience directly. It is only when this information is evaluated through a cognitive filter (for example, a cognitive appraisal of threat, self-presentation, self-efficacy, etc.) that it acquires some significance for the person. Importantly, these filters are considered so powerful that they are believed to be capable of transforming sensory data into very diverse experiences. Consequently, according to these theories, since the mind is what determines the experience, the most effective way of changing the experience is through changing the cognitive processes that occur in the mind. Therefore, biofeedback, a process intended to improve the self-monitoring and self-regulation of bodily functions, is regarded as being of relatively little consequence.

For example, according to Averill (1980), "it is . . . worth emphasizing that [bodily] feedback is subject to second-order monitoring . . . and it is the monitoring that determines the quality of experience, not the feedback per se" (p. 317). Similarly, Bandura (1982) asserted that physiological input "is not inherently enlightening" and can acquire meaning "only through cognitive appraisal" (p. 127). Lazarus has expressed similar ideas. In his view, the physiological input is similar to malleable raw material. Depending on the cognitive interpretation, it can be transformed into diametrically opposite experiences. Using running as an example to illustrate his point, Lazarus (1991) stated that the physiological cues associated with running-induced fatigue can be experienced as distress in a close race because they are interpreted as signs of exhaustion, thus raising the possibility that the race may be lost. However, the same physiological cues may lead to a sense of satisfaction during training because they signify that the body is being strengthened without much being at stake. Thus, it is not surprising that, commenting on the use of biofeedback for emotional regulation, Lazarus (1975, 1977) contended that biofeedback is merely "dealing with the somatic reaction rather than its cause" (Lazarus, 1975, p. 559), whereas the use of cognitive coping strategies constitutes "direct action" that can regulate emotional arousal by actively coping with the appraisals that generated the arousal "in the first place" (p. 559).

These views have been widely echoed within exercise psychology. Authors have commonly suggested that, in order to cope with the intense and unpleasant physiological symptoms associated with strenuous exercise, individuals should try to cognitively "reinterpret" (e.g., McAuley, 1994) or "reframe" (e.g., Hardy & Rejeski, 1989) these symptoms in their minds.

These ideas seem to promote the separation of the mind from the body and, as a result, they have been criticized as dualistic. For example, according to Lee (1995), Bandura's position that physiological activity only acquires meaning after it is cognitively analyzed and interpreted, effectively reduces the individual to "a collection of subjective experiences, with a body more or less tacked on as a way of getting around" (pp. 261–262). Similarly, within exercise psychology, Morgan (1989) has contended that many authors, "especially those who rely exclusively on cognitive psychology, seem to believe that the head does not have a body" (p. 100).

## TIME FOR INTEGRATION?

On the one hand, the studies that have been based on cognitive and social-cognitive theories have offered strong evidence that attention and cognition are important determinants of perceptions of exertion and affective responses to exercise. On the other hand, it would be groundless to refute the importance of physiological input in shaping subjective responses to a *physical* activity, such as exercise. As Brownell (1991) put it, "control over our bodies must be considered within the context of biological realities" (p. 308). Therefore, the challenge lies in developing a conceptual framework that reflects the importance of both cognitive and interoceptive factors and outlines the conditions for their interaction.



A model of perceived exertion proposed by Rejeski (1981) was the first attempt at such an integration. According to this model, the relative influence of cognitive factors and physiological input in shaping perceptions of exertion varies systematically across increasing “doses” of exercise. Specifically, “cognitive variables should be expected to influence [perceived exertion] most when the sport/physical task in question is performed at, or has physiological demands of, a submaximal nature” (p. 314). Beyond this submaximal level, “there is a point in the physical stress of exercise at which sensory cues, due to their strength, dominate perception. Under such conditions, it is unreasonable to expect mediation by psychological factors” (Rejeski, 1985, p. 372). It is unreasonable because “powerful metabolic changes may preclude cognitive manipulations from enabling someone to continue an activity” (Rejeski & Thompson, 1993, p. 18). Considerable empirical evidence has accumulated over the years in support of this idea. For instance, the expectation of a longer versus a shorter exercise duration was shown to lead to significantly lower perceptions of exertion up to the 15th minute, but not during the final 5 min of a demanding 20-min run at 85% of maximal aerobic capacity (Rejeski & Ribisl, 1980). Also, contrary to what was seen with exercise at 60% and 75% of maximal heart rate, attentional manipulations by means of music and sensory deprivation had no effects on perceptions of exertion at 85% of maximal heart rate (Boutcher & Trenske, 1990). Similarly, the presence of a coactor appeared to be associated with suppressed perceptions of exertion at 25% and 50%, but not at 75% of maximal aerobic capacity (Hardy, Hall, and Prestholdt, 1986).

The conceptual approach taken in the present review is generally consistent with the postulates of Rejeski’s (1981) model. Specifically, we believe that exertional and affective experiences during exercise are a function of both cognition and direct interoception (i.e., the cognitively unmediated perception of physiological functions by the brain). Although both of these ingredients are necessary, we also believe that the relative importance of these two factors changes as a function of exercise intensity. Specifically, we speculate that cognition plays the primary role in low and moderate exercise intensities and direct interoception becomes the dominant influence at high and near-maximal intensities.

As noted earlier, research on exercise-induced affect has shown that, as exercise intensity increases, there are systematic declines in affective valence. Furthermore, it is noteworthy that, although interindividual variability in ratings of affective valence tends to be large at moderate and moderately high exercise intensities, it is suppressed considerably when the intensity approaches the individuals’ functional limits (Hall, Ekkekakis, & Petruzzello, 2002). In these situations, there is a universally negative affective response.

From a practical standpoint, the challenge, as we see it, is to educate exercisers, particularly those who are just beginning an exercise program and are “interoceptively naive,” to recognize the early signs of physiological strain and to self-regulate the intensity of their efforts accordingly. This is necessary given the fact that, beyond this level of intensity, the capacity to alter the nature of subjective experiences through cognitive coping methods is progressively reduced. In our view, biofeedback can play

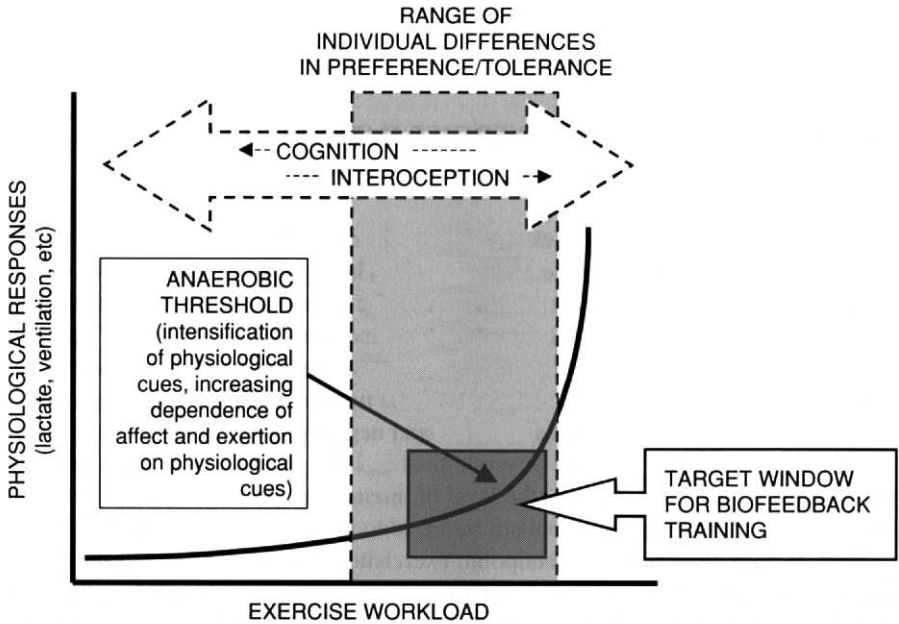
a significant role in this regard by sharpening the individuals' sense of interoceptive acuity.

## SEEKING THE OPTIMAL EXERCISE INTENSITY FOR FITNESS, ENJOYMENT, AND ADHERENCE

Before deciding to use biofeedback to train exercisers to self-monitor and self-regulate the intensity of their efforts, one is faced with a key question: what is the optimal level of exercise intensity? In other words, what are the elusive signs of physiological strain that novice exercisers should be taught to recognize? In selecting the "optimal" level of exercise intensity for healthy populations, two factors must be considered and balanced: the need for effective training and the need to avoid aversive experiences (i.e., excessive levels of perceived exertion and negative affective responses). There is converging evidence from the physiological and the psychological literatures that the point of balance may be near the level of intensity associated with the transition from aerobic to anaerobic metabolism (referred to as the "anaerobic threshold").

First, from a *physiological* standpoint, exercising at an intensity that exceeds the anaerobic threshold has not been shown to confer any additional fitness benefits compared to exercise performed at or slightly below this threshold among previously untrained individuals (Belman & Gaesser, 1991; Weltman, Seip, Snead, Weltman, Haskvitz, Evans, Veldhuis, & Rogol, 1992). Second, from a *psychological* standpoint, preliminary studies from young and physically active participants have shown that exercising above the individually determined anaerobic threshold (defined as the ventilatory or gas exchange threshold) is associated with significant declines in the valence of affective responses (Hall et al., 2002). Studies on perceived exertion have also shown that the intensity of exercise that corresponds to the anaerobic threshold is typically rated as "somewhat hard" or "hard", whereas exercise performed at intensities below the anaerobic threshold is rated as "light" (DeMello, Cureton, Boineau, & Singh, 1987; Hetzler, Seip, Boutcher, Pierce, Snead, & Weltman, 1991; Hill, Cureton, Grisham, & Collins, 1987; Purvis & Cureton, 1981). According to Robertson (1982), on the basis of the differences in the nature and the substrates of perceived exertion, three levels of exercise intensity can be distinguished. In level I, where the metabolic rate is less than 50%  $VO_{2max}$ , perceived exertion reflects mainly proprioception and movement awareness. Level II, where the metabolic rate is near the anaerobic threshold (i.e., 50–70%  $VO_{2max}$ ) and the ventilatory drive begins to contribute substantially to perceptions of exertion, is characterized as "uncomfortable, but tolerable." Finally, level III, where the metabolic rate exceeds the anaerobic threshold and the ventilatory drive is a very significant contributor to perceptions of exertion, is characterized as "painful or unpleasant" (Noble & Robertson, 1996, p. 395).

These observations point to some important conclusions. First, the level of exercise intensity that corresponds to the transition from aerobic to anaerobic metabolism appears to be a good candidate for a target exercise intensity, since it seems to maximize the physical training benefit without compromising affective responses, at least among



**Figure 5.3** Proposed target of biofeedback training for healthy populations. Biofeedback training should be primarily aimed at teaching exercisers to recognize the transition from aerobic to anaerobic metabolism and to maintain an exercise intensity that approximates this level (within a range of individual preferences and tolerance). Beyond this level, perceived exertion and negative affective responses become progressively more dependent on physiological cues and, thus, not easily manageable through cognitive techniques.

individuals with a positive or nonnegative attitude or predisposition toward exercise. Second, the physiological, primarily ventilatory, markers of the aerobic–anaerobic transition, which become increasing salient following the transition, appear to be the most relevant candidates for biofeedback training (Figure 5.3).

## PROBLEMS WITH CURRENTLY USED METHODS FOR SELF-REGULATING EXERCISE INTENSITY

When exercise is performed under expert supervision in a clinical setting, devices such as heart rate monitors (Gilman & Wells, 1993) and portable lactate analyzers (Fell, Rayfield, Gulbin, & Gaffney, 1998; Pyne, Boston, Martin, & Logan, 2000) can be used to monitor physiologic responses and guide the selection of intensity. Similarly, the development of commercial heart-rate-based servo-controlled exercise equipment (Jacobsen & Johansen, 1974; Kawada, Sunagawa, Takaki, Shishido, Miyano, Miyashita, Sato, Sugimachi, & Sunagawa, 1999; Laperriere, VanDercar, Shyu, Ward, Mc Cabe, Perry, Mosher, & Schneiderman, 1989; Pratt, Siconolfi, Webster, Hayes,

Mazzocca, & Harris, 1991) creates the possibility of automated regulation of intensity in fitness and rehabilitation centers. However, these solutions are not cost-effective and cannot be applied on a large scale. When exercise is performed in unsupervised settings, as is usually the case with healthy adults, there is a need for self-regulatory methods that are inexpensive, easy to understand and implement, and can be applied without the benefit of continuous physiological monitoring.

At present, the most frequently used methods for self-monitoring and self-regulating the intensity of physical activity are the palpation of heart beat and the use of rating scales of perceived exertion (American College of Sports Medicine, 2000). Both methods are simple and can be relatively effective, but both also have some recognized limitations.

Methods based on heart rate can be problematic due to the large inter- and intraindividual variability of submaximal heart rates (Chow & Wilmore, 1984). In addition, heart rate is a poor index of the metabolic characteristics of physical effort (i.e., whether primarily aerobic or anaerobic mechanisms are involved). For example, in a study of 20 untrained college women, Dwyer and Bybee (1983) reported that, when cycling at 75%, 80%, and 85% of heart rate reserve, 9, 13, and 15 participants, respectively, were using anaerobic metabolism, whereas the rest were using aerobic metabolism. Likewise, Katch, Weltman, Sady, and Freedson (1978) reported that, in a sample of 31 participants, when exercise was performed at 80% of maximal heart rate, 17 participants were using primarily anaerobic metabolism, whereas 14 were using primarily aerobic metabolism.

By using heart rate as a method of monitoring exercise intensity and, thus, having no information on aerobic-anaerobic balance, exercisers may inadvertently drift into anaerobic metabolism, experiencing an affectively aversive and cognitively unmanageable surge of salient interoceptive cues. Almost 20 years ago, Dwyer and Bybee (1983) recognized that this may have important implications for exercise adherence: "... compliance to a voluntary training program may be influenced by indiscriminately prescribed exercise that requires an individual to exercise considerably above his [sic] anaerobic threshold and to experience the subjective discomforts associated with exercise at that level" (p. 75).

The effectiveness of methods based on perceived exertion can also be questioned. Correlations between ratings of perceived exertion and physiological indices like oxygen uptake, heart rate, or blood lactate are often low (Potteiger & Evans, 1995; Thompson & West, 1998; Whaley & Forsyth, 1990), particularly at low and moderate levels of intensity (Borg, Ljunggren, & Ceci, 1985; Eston, Davies, & Williams, 1987; Eston & Williams, 1988; Green, Michael, & Solomon, 1999; Smutok, Skrinar, & Pandolf, 1980). This is important, given that this is the range of intensity typically prescribed to beginner exercisers. Studies have also shown that the accuracy of perceptions of exertion may change across different situations; for example, between exercise testing in a clinical setting and rehabilitation training in the field (Bayles, Metz, Robertson, Goss, Cosgrove, & McBurney, 1990; Brubaker, Rejeski, Law, Pollock, Wurst, & Miller, 1994; Gutmann, Squires, Pollock, Foster, & Anholm, 1981) or between different exercise protocols (Whaley, Woodall, Kaminsky, & Emmett, 1997).

Recognizing that, under certain conditions, ratings of exertion are not accurate indices of actual physiological effort, Dishman (1994) warned that reliance on this method may have a negative impact on exercise adherence. He asked, "How can we teach [people] to more accurately estimate and produce a prescribed exercise intensity? What is the impact of RPE errors on inactivity or on risk of injury?" (p. 1092). However, these questions remain unanswered.

## BIOFEEDBACK RESEARCH IN THE CONTEXT OF EXERCISE

As noted previously, the number of studies that have examined the effectiveness of biofeedback for regulating exercise intensity is relatively small. Most of these studies have used heart rate as a biofeedback channel. This is in spite of the fact that cardiac activity is not directly accessible to conscious awareness. As several studies have shown, when asked to detect or discriminate their cardiac activity without previous training, most people perform poorly, at levels not much better than those attained by chance (see Jones, 1994, for a review).

According to Hollandsworth (1979), exercise is essentially a natural analogue to instrument-based biofeedback, as it performs the same function, namely the amplification of physiological signals, in a natural way. In fact, it has been shown that, following vigorous exercise, participants report increased awareness of their physiological state (Hollandsworth & Jones, 1979). Moreover, Jones and Hollandsworth (1981) found that the ability of physically inactive and moderately active (tennis players) participants to discriminate their cardiac activity improved (to above-chance levels) following exercise that raised their heart rates by 75% over baseline. On the other hand, highly trained male distance runners (running over 25 miles per week) did not improve their discrimination accuracy after exercise, but still fared consistently better than their inactive and moderately active counterparts both at baseline and after exercise. This finding was consistent with Hollandsworth's (1979) prediction that, by using running as a natural biofeedback, experienced runners would also be able to monitor and possibly control their physiological responses at resting conditions. However, this finding was not replicated. Montgomery, Jones, and Hollandsworth (1984) found that average-fitness participants achieved above-chance discrimination accuracy both during and after exercise (120–130 beats/min or approximately 65% of age-predicted maximal heart rate), whereas high-fitness participants achieved above-chance accuracy only after exercise. Contrary to the findings of Hollandsworth and Jones (1979), the groups did not differ at baseline. Furthermore, Montgomery et al. (1984) noted that the lower accuracy of the high-fitness group during exercise appeared to be due to inaccurate expectancies. Specifically, the high-fitness participants accepted heart rate feedback that was 30% lower than their actual heart rate as accurate on 79% of the presentations, whereas the corresponding figure for the average-fitness group was only 58%. In another study, Gillis and Carver (1980) failed to find support for the hypothesis that participants high in dispositional self-consciousness or with

situationally elevated self-consciousness (as a result of exercising in front of a mirror) would show higher accuracy in estimating their heart rates after exercise.

Another series of studies examined whether traditional, instrument-based biofeedback training during exercise can help participants lower their physiological responses to exercise without reducing the amount of work being performed. In the first such study, Goldstein, Ross, and Brady (1977) found that five sessions of heart rate biofeedback training resulted in significant reductions in heart rate, systolic blood pressure, and rate-pressure product while walking on a treadmill. Furthermore, when the treatment was removed, the participants were able to maintain the reduced levels of heart rate, systolic blood pressure, and rate-pressure product. However, when the participants in the control group were subsequently introduced to biofeedback, they failed to show similar reductions.

Perski and Engel (1980) attempted to replicate the findings of this first study. They found that five heart rate biofeedback training sessions led to the experimental group having a heart rate that was significantly lower (by 15.2 beats/min or approximately 20%) compared to the control group during fixed-workload cycle ergometry exercise. Contrary to the findings of Goldstein et al. (1977), Perski and Engel found that, after the members of the control group underwent five sessions of biofeedback training, they were also able to significantly reduce their heart rate (by 13 beats/min). Finally, after the biofeedback treatment was removed for two sessions, the members of the experimental group were able to maintain the reduction in heart rate. On the other hand, biofeedback did not seem to have an effect on systolic blood pressure.

The exercise intensity used in Perski and Engel's (1980) study was approximately 50% of age-predicted maximal heart rate. In a follow-up study, Perski, Tzankoff, and Engel (1985) examined whether the findings could be replicated with a more vigorous exercise stimulus, namely 65% of maximal heart rate. After four training sessions during which they exercised while receiving heart rate biofeedback, the members of the experimental group showed an average heart rate elevation that was smaller by about 22% (12 beats/min) compared to the control group. On the other hand, there were no differences in systolic blood pressure. After the control participants underwent biofeedback training for four sessions, they also reduced their heart rates by about 9% (5 beats/min). Interestingly, additional analyses showed that the smaller heart rate elevations were not accompanied by compensatory physiological adjustments. There were no statistically significant differences in oxygen consumption, lactate accumulation, or indices of sympathetic nervous system activity (plasma epinephrine and norepinephrine concentrations). On the contrary, the lower heart rate was accompanied by lower pulmonary ventilation. Comparisons were also made during graded maximal tests performed before and after biofeedback training (the experimental group and the initial control group after biofeedback training were combined). In this case, both at a submaximal (75% of maximal heart rate) and at the maximal level, systolic blood pressure and rate-pressure product were lower after biofeedback training, but there were no significant changes in heart rate. Again, there were no signs of compensatory physiological adjustments, as there were no significant differences

in ventilation, respiratory quotient, oxygen consumption, lactate accumulation, or epinephrine or norepinephrine concentration.

Studies by Lo and Johnston compared biofeedback to relaxation and also examined the role of instructions and habituation. In one study (Lo & Johnston, 1984a), an instructions-only condition, an inter-beat-interval (IBI) biofeedback condition, and a condition involving feedback on the product of IBI and pulse transit time (PTT) were compared. This product is almost perfectly negatively correlated with the rate-pressure product and is decreased with exercise. With respect to changes in IBI, four training sessions of IBI by PTT product biofeedback were significantly more effective than verbal instructions in increasing IBI (lowering heart rate). IBI-only biofeedback had intermediate effects and was associated with a gradual improvement across training sessions, but did not differ significantly from the other two conditions. The instructions-only condition was not associated with any changes. With respect to changes in PTT, both the IBI by PTT biofeedback condition and the IBI-only condition led to greater increases in the IBI by PTT product compared to instructions. Again, the instructions-only condition was not associated with any changes. The positive effects of biofeedback did not seem to transfer well, however, after the feedback was withdrawn. During a no-feedback fifth session, there were no differences between the conditions.

In another study, Lo and Johnston (1984b) compared the effects of IBI by PTT biofeedback to habituation (simply exercising) and Benson's relaxation response. Two exercise and two nonexercise training sessions were conducted. Compared to exercise before treatment, the biofeedback condition was associated with increases in IBI and was significantly different from both other conditions. With respect to PTT, the feedback condition was superior to habituation, whereas the relaxation condition was intermediate but did not differ significantly from the other two conditions. Only the feedback condition was associated with an improvement across trials. Finally, the frequency of respiration was slower in the feedback condition compared to the other two conditions.

Yamaji, Yokota, and Shephard (1992) conducted a case series study to examine the effects of using wrist-mounted heart rate monitors during track and cross-country training on the accuracy of heart rate estimations during different modes of exercise (treadmill, cycle ergometer, stair climber). Six runners wore heart rate monitors during their regular training (2 h/day, 3–4 days/week). Before and after a period of 13 weeks of training, they participated in multiple graded tests to exhaustion on a treadmill, a cycle ergometer, and a stair climber. The error of estimation (the discrepancy between perceptions of heart rate and ECG) improved in 6 of the 6 runners during treadmill running, in 4 of the 6 during cycle ergometry, but in only 2 of the 6 in stair climber exercise. After training, the regression lines of estimated and ECG-determined heart rate were closer to the line of identity in 6 of 6 treadmill tests, 5 of 6 cycle ergometer tests, and in 4 of 6 stair climber tests. In general, the discrepancies decreased with increasing exercise intensity.

Another study (Sada, Hamada, Yonezawa, & Ninomiya, 1999) examined the effects of a simple device designed to alert exercisers (with lights and sounds) when they

exceeded a predetermined heart rate. Seven healthy males ran on a treadmill for five 6-min periods, while the target heart rate was set at 80, 100, 120, 140, and 160 beats/min, respectively. The participants overshot their target heart rates in 21 s when the target was 80 beats/min, in 40 s when the target was 120 beats/min and in 102 s when the target was 160 beats/min. Using the alarms, the participants adjusted their stride length and frequency and were able to keep their heart rates within 10% for a target heart rate of 80 beats/min, and within 4% for a target heart rate of 100–160 beats/min.

Two studies have examined the effects of noncardiovascular biofeedback. Kirkcaldy and Christen (1981) examined the effects of frontalis EMG biofeedback. They randomly assigned 26 male participants to one of four conditions: (a) frontalis EMG biofeedback during resting conditions (no exercise), (b) frontalis EMG biofeedback following exercise, (c) pseudo-feedback during resting conditions (no exercise), and (d) Jacobson's progressive relaxation during resting conditions (no exercise). Five training sessions were conducted. There were also five testing sessions, during which the participants performed one 8-min incremental bout of cycle ergometry (from 30 to 150 W). The first was a pretest, followed by a 15-min passive recovery. The second and third were interspersed with the training sessions and the fourth was a post-test. In these sessions, the first 10 min of post-exercise recovery were replaced by an application of the respective techniques. The fifth session was conducted seven weeks later, did not involve instrumentation, and its purpose was to test for retention. Only the group that received frontalis EMG biofeedback following exercise showed a reduction in frontalis muscle tension across sessions following exercise. At the post-test session, the mean EMG of the two biofeedback groups was significantly lower than the mean of the pseudo-feedback group, whereas the relaxation group showed a nonsignificant increase in tension. However, at the seven-week follow-up session, conducted without the benefit of biofeedback instrumentation, there were no signs of retention.

Hatfield, Spalding, Mahon, Slater, Brody, & Vaccaro (1992) examined the effects of providing biofeedback on the ventilatory equivalent for oxygen ( $V_E/V_{O_2}$ ) and the EMG activity of the trapezius muscle during running. A group of 12 male collegiate runners ran on a treadmill for three consecutive 12-min periods at an intensity that was just below their ventilatory threshold ( $71\% V_{O_{2max}}$ ). During one period, they received  $V_E/V_{O_2}$  and EMG biofeedback. During another period, their attention was distracted by means of a coincident timing task. Finally, one period did not involve a manipulation of the runners' attentional set and was used as a control. The results showed that  $V_E/V_{O_2}$ , the ventilatory equivalent of carbon dioxide ( $V_E/V_{CO_2}$ ), ventilation, and respiratory rate were lower and tidal volume was higher during biofeedback than during the attentional distraction and control periods. Interestingly, despite the fact that ventilation was reduced during the biofeedback period, there were no differences in oxygen uptake between conditions, which suggests that there was a greater extraction of oxygen from inspired air per breath during biofeedback. Furthermore, the ratings of perceived exertion were lower during feedback and distraction compared to control. On the other hand, no effects on EMG were found.

The studies summarized up to this point all involved healthy participants. Positive effects, however, have also been found in cardiovascular patients. In an early



uncontrolled case series study, Johnston and Lo (1983) examined 7 angina patients who underwent between 3 and 12 IBI by PTT biofeedback training sessions. All the patients were able to increase the IBI by PTT product while at rest but not during exercise. However, the frequency of chest pains was reduced in six of seven patients, the use of glycerine trinitrate (nitroglycerine) was reduced in all seven, and exercise tolerance during a Bruce protocol was improved in six of seven. In a subsequent study, Fredrikson and Engel (1985) examined 12 hypertensive patients. Half of them underwent five heart rate biofeedback training sessions. On average, their heart rate during exercise was approximately 9 beats/min lower than in control participants. Furthermore, although there were no differences in exercise workload, the biofeedback group showed lower oxygen consumption near the end of training. On the other hand, the groups did not differ in systolic blood pressure.

To date, there have been no extensive studies on the effects of biofeedback during strength training in humans. Johnston, Lo, Marie, and Van Jones (1982) briefly reported the results of a study comparing verbal instruction to decrease blood pressure to PTT biofeedback during 30 s of a 50% of maximal voluntary contraction with a hand grip dynamometer and a 60-s recovery period. Despite a tendency of the biofeedback condition to elicit longer IBIs and PTTs, the differences were not statistically significant. However, a series of studies in monkeys by Engel, Talan, and their associates suggests that a combination of heart rate biofeedback (a light indicating that heart rate was in the desired range) and operant conditioning (food reward and shock avoidance) can be effective in lowering heart rate and rate-pressure product while performing repeated weight lifts (see Engel & Talan, 1991a, for a review). The monkeys were trained to lift weights, to lower their heart rates, and finally to reliably combine these two skills (Engel & Talan, 1991b; Talan & Engel, 1986). The animals were able to attenuate the exercise-induced increases in heart rate in the combined condition while maintaining their cardiac output. This constitutes evidence of improved cardiac efficiency. Furthermore, the animals had lower respiratory quotient values during the combined condition (although this was due to greater oxygen uptake in two animals and lower carbon dioxide production in one animal). The attenuation of exercise-induced increases in heart rate was unaffected by  $\alpha$ - and  $\beta$ -adrenergic and vagal blockades (Engel & Talan, 1991c), suggesting that the attenuation was not dependent on a specific autonomic reflex. Finally, Chefer, Talan, and Engel (1997) attempted to identify the brain centers that are responsible for the operant conditioning of heart rate by electrically stimulating 24 brain centers known to be involved in the regulation of heart rate (mainly thalamic and limbic nuclei) while the monkeys were performing the combined exercise-heart rate reduction task. Through this process, they identified a system (including the cingulate cortex, the mediodorsal nucleus, and the nucleus ventralis anterior) which increased heart rate when stimulated, but whose effect was significantly attenuated when the animals attempted to lower their heart rates. Chefer et al. expressed the belief that this system plays an important role in the central command of cardiovascular adaptations to exercise.

In summary, although the number of biofeedback studies that have been conducted in the context of exercise is not large and the methodological rigor of these studies

varies widely, the results have been consistent. It appears that as few as four or five biofeedback training sessions may bring about a significant attenuation of exercise-induced increases in heart rate and rate–pressure product. It is also noteworthy that this effect appears to be the result of increases in the efficiency of cardiac function, as it cannot be explained by improvements in fitness, reductions in the amount of work performed, habituation to the experimental settings, or compensatory physiological adjustments. In other words, the benefits of biofeedback do not seem to be accompanied by any negative side effects. Furthermore, on the basis of the few studies conducted so far, it seems that biofeedback may be more effective for controlling cardiovascular responses during exercise than are verbal instructions or relaxation. On the other hand, there are other important questions that remain unanswered. The studies that used noncardiovascular channels as biofeedback sources are too few to allow for any definitive conclusions. Nevertheless, the study by Hatfield et al. (1992), in which biofeedback was based on the ventilatory equivalent for oxygen, produced some promising results. Even without having received training in using this parameter as biofeedback, the runners in the study were able to reduce several ventilatory parameters without reducing the amount of work being produced. Finally, much research is still needed to determine whether biofeedback can help regulate the physiological responses to weight training in humans. The pioneering studies by Engel and Talan (1991a) in monkeys suggest that this is possible.

## **THE PHENOMENOLOGY OF EXERCISE: BIOFEEDBACK WITHOUT INSTRUMENTS?**

As noted previously, most biofeedback studies in the context of exercise have concentrated on heart rate as a biofeedback channel, in spite of the fact that without the benefit of instrumentation most people's ability to perceive their heart beats seems to remain modest even during exercise. However, decades of research on perceived exertion have demonstrated that there are a number of interoceptive cues (mainly associated with ventilation and muscular fatigue) that people can and do use in estimating their exertion levels during exercise (Sime, 1985). As we explained in a previous section, we are particularly interested in the transition from aerobic to anaerobic metabolism because this level of intensity appears to maximize the training benefits for previously untrained individuals without eliciting uniformly negative affective responses. From this perspective, it is noteworthy that the lactate and ventilatory thresholds, commonly used as indices of the aerobic–anaerobic transition, have been found to correspond to stable ratings of exertion that are generally unaffected by gender, training, or exercise modality (DeMello et al., 1987; Hetzler et al., 1991; Hill et al., 1987; Purvis & Cureton, 1981). In conjunction with the finding that exceeding the ventilatory threshold seems to be associated with an almost uniform decline in affective valence (Hall et al., 2002), these findings raise the possibility of using specific, individually determined ratings of perceived exertion and affective valence as targets for “interoceptive acuity” training, as a proxy to conventional, instrument-based biofeedback.

In the only known study to examine the effects of using feedback based on perceptions of exertion, Bayles et al. (1990) randomly assigned 30 participants to a practice-with-feedback group, a practice-without-feedback group, and a control group. Initially, all participants underwent a graded treadmill test. In a second session, each participant ran for 10 min at 40%, 60%, and 80% of their heart rate reserve in random order. During each trial, participants were "encouraged to internalize" their "subjective feelings" and "assign an overall perceptual rating to those sensations" (p. 27). During three subsequent trials, the participants were instructed to reproduce the exercise intensities "based on targeted perceptual ratings that they had assigned to the respective exercise intensities in trial 1" (p. 27). During a week between trials 2 and 3, the practice-with-feedback group and the practice-without-feedback group participated in a learning program which consisted of three periods. Also, during a week between trials 3 and 4, these groups participated in three exercise sessions on an indoor track at intensities that were individually selected to produce exertional sensations that were the same as those experienced during the treadmill exercise at 60% of heart rate reserve. Compared to the practice-without-feedback group, the practice-with-feedback group received taped reminders to think about (a) body temperature, (b) breathing, (c) comfort level, and (d) motivation. The main finding was that the practice-with-feedback group and the practice-without-feedback group both reduced their percent inaccuracy scores for running speed by 4.5% by trial 3 (averaged across the three intensities), whereas the control group increased their percent inaccuracy scores for running speed by 4.5%. For all three groups, the level of inaccuracy was maintained from trial 3 to trial 4. However, no effect on percent inaccuracy scores for heart rate or oxygen uptake was observed. Furthermore, it was found that the replication of heart rate and oxygen uptake values was more accurate at 60% and 80% of heart rate reserve compared to 40%.

Clearly, this area of research is in need of more information. Important questions that need to be addressed include (a) whether the combination of affect and exertion ratings can lead to improved self-regulation compared to methods based only on perceived exertion and (b) whether the relatively salient interoceptive cues that accompany the aerobic-anaerobic transition can serve as universal perceptual landmarks.

An important first step should be the systematic exploration of what has been called the "subjective symptomatology" or "phenomenology" of exercise (Dishman, 1994) and the aerobic-anaerobic transition, in particular. The present understanding of the subjective experiences that accompany exercise of various intensities remains very limited. In fact, not much progress has been made in this area since the pioneering studies by Kinsman and Weiser in the early 1970s (Kinsman & Weiser, 1976; Kinsman, Weiser, & Stamper, 1973; Weiser, Kinsman, & Stamper, 1973). This work was based on multivariate statistical methods (cluster and spherical analyses) that yield multidimensional representations of the relationships between perceived "symptoms" or cues associated with exercise. The results showed that the interoceptive and affective cues associated with exercise form distinct clusters, with each cluster contributing unique portions of the variance. However, this investigation was limited in several

respects. First, it was based on a given list of items which may or may not adequately reflect the subjective experiences of diverse samples of exercise participants. Second, it was based on cycle ergometer exercise which emphasizes sensations localized in the legs and, thus, the results may not be generalizable to other modes of activity. Third, exercise intensity was based on an arbitrary percentage of maximal aerobic capacity and did not take into account the balance between aerobic and anaerobic metabolism. Fourth, no attempt was made to examine whether the emergent clusters could be used to differentiate between different levels of exercise intensity.

In spite of the limitations of this early research, it should be apparent that developing a better understanding of the subjective experiences associated with exercise, their verbal descriptors, and their dimensionality should improve communication between researchers and practitioners, as well as between practitioners and the public. The lack of this information is particularly noticeable in clinical applications of exercise. As one shocking example, there has never been a systematic exploration of the perceptual cues that can reliably distinguish between natural exertional symptoms and symptoms of exertional angina in cardiac patients. In the absence of this information, exercise practitioners have no basis upon which to educate patients on the cues that they can use to properly self-monitor and self-regulate the intensity of their physical activity.

## FUTURE DIRECTIONS

Based on our review of this area of research, we propose the following. The first requisite step is an expansion of the current theoretical perspectives that consider the mind as the sole determinant of human experiences in the context of exercise. Instead, we advocate the development of integrative conceptual models that acknowledge the joint contributions of cognition and direct interoception in the process of generating subjective experiences in response to exercise.

Second, we believe that the research paradigm used in biofeedback studies in the context of exercise should be shifted from *visceral detection* to *visceral perception* (Pennebaker & Hoover, 1984). In other words, biofeedback training should incorporate perceived exertion and affective responses in addition to direct indices of physiological activity. Research suggests that, although it may be difficult for many individuals to accurately monitor isolated physiological parameters such as heart rate or blood pressure without extensive training, the accurate monitoring of the “gestalt” of exertional symptoms may be easier to achieve and, thus, more effective from a practical standpoint. In particular, the intensification of exertional symptoms and the negative shift in affective valence that accompany the transition to anaerobiosis may be used as “anchor points” to facilitate the training process.

Third, the study of the “subjective symptomatology” of exercise (Kinsman & Weiser, 1976; Kinsman et al., 1973; Weiser et al., 1973) must be revived and extended to a variety of exercise stimuli and populations, including patient populations

with exercise-limiting conditions. The utility of this research should be obvious and its revival is long overdue.

Fourth, the utility of alternative physiological channels as sources of biofeedback should be explored. In addition to ventilatory parameters (Hatfield et al., 1992), it may be useful to examine the utility of blood lactate assessments. Although it remains impossible to assess blood lactate concentrations in real time, the advent of relatively inexpensive and simple-to-use portable lactate analyzers (Fell et al., 1998; Pyne et al., 2000) that yield results in 60 s creates some interesting possibilities. These analyzers may provide the easiest method of detecting the transition to anaerobic metabolism. The error grid technique used in the regulation of blood glucose in diabetics (Gonder-Frederick & Cox, 1991) could be adapted for the monitoring and regulation of lactate in the context of exercise. This simple technique involves plotting the estimated and assessed levels of lactate on a grid and noting the degree of deviation from the line of identity. Through the repeated use of the error grid and training in using pertinent sources of information, such as perceived exertion and affect, exercisers may improve their self-monitoring skills. The application of this method for the regulation of blood glucose has produced some promising results (Gonder-Frederick & Cox, 1991) that warrant attention.

For theoretical and practical reasons alike, biofeedback deserves more attention within exercise psychology than it has received until now. Undoubtedly, much work remains to be done. However, based on the positive findings that have accrued so far, it appears that biofeedback may be an effective method of improving the self-monitoring and self-regulation of exercise intensity in both healthy and clinical populations. By doing so, biofeedback may play a significant role in making exercise safer and more enjoyable and may, thus, contribute to the much-needed increase in the rates of adherence to exercise over the long haul.

## CONCLUDING SUMMARY

The field of exercise psychology faces the great challenge of having to develop conceptual models to help understand exercise behavior and intervention methods for increasing exercise participation and long-term adherence. One mechanism that is likely to influence exercise behavior but has received relatively little attention is one in which a critical role is attributed to the intensity of exercise and its effects on the quality of the experience that participants derive from their involvement. On the one hand, if the intensity of exercise is too low, the possibility of substantial health and fitness benefits is reduced, increasing the likelihood of dropout due to frustration stemming from unfulfilled expectations. On the other hand, if the intensity of exercise is too high (according to accumulating evidence, if it exceeds the point of transition from aerobic to anaerobic metabolism), most individuals report feeling progressively worse and rate the intensity as "hard." Over time, such unpleasant experiences may lead to an aversion to exercise, again raising the possibility of dropout. The conclusion that emerges is that accurate self-monitoring and self-regulation of exercise intensity

could have a significant impact on subsequent exercise behavior by influencing the quality of the experience that individuals derive from exercise.

In this context, biofeedback can prove to be a powerful tool for teaching exercisers to maintain the delicate balance between exercise intensity that is effective on the one hand and pleasant or tolerable and safe on the other. The studies on the effects of biofeedback in the context of exercise are few, but have consistently demonstrated that even as little as four or five sessions of biofeedback training can attenuate the exercise-induced increases in physiological activation without reducing the amount of work being performed. From an applied standpoint, it is also important that these effects seem to be the results of improved efficiency in physiological function, as there have been no indications of negative side effects, such as compensatory physiological adjustments. Although the extant evidence supports the use of biofeedback in practice, research should continue and its scope should be expanded, placing emphasis on the use of noncardiovascular (e.g., ventilatory, blood lactate, etc.) biofeedback modes, the linkage of biofeedback to exertional and affective experiences, and the investigation of the content, the verbal descriptors, and the dimensionality of such experiences.

## REFERENCES

- Acevedo, E. O., Rinehardt, K. F., & Kraemer, R. R. (1994). Perceived exertion and affect at varying intensities of running. *Research Quarterly for Exercise and Sport*, **65**, 372–376.
- American College of Sports Medicine (2000). *ACSM guidelines for exercise testing and prescription* (6th ed.). Baltimore, MD: Williams & Wilkins.
- Averill, J. R. (1980). A constructivist view of emotion. In R. Plutchik & H. Kellerman (eds.), *Emotion: Theory, research, and experience* (vol. 1; pp. 305–339). New York: Academic.
- Bandura, A. (1982). Self-efficacy mechanism in human agency. *American Psychologist*, **37**, 122–147.
- Bayles, C. M., Metz, K. F., Robertson, R., Goss, F. L., Cosgrove, J., & McBurney, D. (1990). Perceptual regulation of prescribed exercise. *Journal of Cardiopulmonary Rehabilitation*, **10**, 25–31.
- Belman, M. J., & Gaesser, G. A. (1991). Exercise training below and above the lactate threshold in the elderly. *Medicine and Science in Sports and Exercise*, **23**, 562–568.
- Borg, G., Ljunggren, G., & Ceci, R. (1985). The increase of perceived exertion, aches and pain in the legs, heart rate and blood lactate during exercise on a bicycle ergometer. *European Journal of Applied Physiology*, **54**, 343–349.
- Boutcher, S. H., & Trenske, M. (1990). The effects of sensory deprivation and music on perceived exertion and affect during exercise. *Journal of Sport & Exercise Psychology*, **12**, 167–176.
- Brewer, B. W., Manos, T. M., McDevitt, A. V., Cornelius, A. E., & Van Raalte, J. L. (2000). The effect of adding lower intensity work on perceived aversiveness of exercise. *Journal of Sport & Exercise Psychology*, **22**, 119–130.
- Brownell, K. D. (1991). Personal responsibility and control over our bodies: When expectation exceeds reality. *Health Psychology*, **10**, 303–310.
- Brubaker, P. H., Rejeski, W. J., Law, H. C., Pollock, W. H., Wurst, M. E., & Miller, H. S. (1994). Cardiac patients' perception of work intensity during graded exercise testing: Do they generalize to field settings? *Journal of Cardiopulmonary Rehabilitation*, **14**, 127–133.

- Chefer, S. I., Talan, M. I., & Engel, B. T. (1997). Central neural correlates of learned heart rate control during exercise: Central command demystified. *Journal of Applied Physiology*, **83**, 1448–1453.
- Chow, R. J., & Wilmore, J. H. (1984). The regulation of exercise intensity by ratings of perceived exertion. *Journal of Cardiac Rehabilitation*, **4**, 382–387.
- DeMello, J. J., Cureton, K. J., Boineau, R. E., & Singh, M. M. (1987). Ratings of perceived exertion at the lactate threshold in trained and untrained men and women. *Medicine and Science in Sports and Exercise*, **19**, 354–362.
- Desharnais, R., Bouillon, J., & Godin, G. (1986). Participants' early impressions of a supervised exercise program as a determinant of their subsequent adherence. *Perceptual and Motor Skills*, **64**, 847–850.
- Dishman, R. K. (1994). Prescribing exercise intensity for healthy adults using perceived exertion. *Medicine and Science in Sports and Exercise*, **26**, 1087–1094.
- Dishman, R. K., & Buckworth, J. (1996). Increasing physical activity: A quantitative synthesis. *Medicine and Science in Sports and Exercise*, **28**, 706–719.
- Dwyer, J., & Bybee, R. (1983). Heart rate indices of the anaerobic threshold. *Medicine and Science in Sports and Exercise*, **15**, 72–76.
- Ekkekakis, P., & Petruzzello, S. J. (1999). Acute aerobic exercise and affect: Current status, problems, and prospects regarding dose-response. *Sports Medicine*, **28**, 337–374.
- Emmons, R. A., & Diener, E. (1986). A goal-affect analysis of everyday situational choices. *Journal of Research in Personality*, **20**, 309–326.
- Engel, B. T., & Talan, M. I. (1991a). Cardiovascular responses as behavior. *Circulation*, **83** [Supplement II], 9–13.
- Engel, B. T., & Talan, M. I. (1991b). Hemodynamic and respiratory concomitants of learned heart rate control during exercise. *Psychophysiology*, **28**, 225–230.
- Engel, B. T., & Talan, M. I. (1991c). Autonomic blockade does not prevent learned heart rate attenuation during exercise. *Physiology and Behavior*, **49**, 373–382.
- Epstein, L. H., Koeske, R., & Wing, R. R. (1984). Adherence to exercise in obese children. *Journal of Cardiac Rehabilitation*, **4**, 185–195.
- Eston, R. G., Davies, B. L., & Williams, J. G. (1987). Use of perceived effort ratings to control exercise intensity in young healthy adults. *European Journal of Applied Physiology*, **56**, 222–224.
- Eston, R. G., & Williams, J. G. (1988). Reliability of ratings of perceived effort regulation of exercise intensity. *British Journal of Sports Medicine*, **22**, 153–155.
- Fell, J. W., Rayfield, J. M., Gulbin, J. P., & Gaffney, P. T. (1998). Evaluation of the Accusport lactate analyser. *International Journal of Sports Medicine*, **19**, 199–204.
- Fredrikson, M., & Engel, B. T. (1985). Learned control of heart rate during exercise in patients with borderline hypertension. *European Journal of Applied Physiology*, **54**, 315–320.
- Gillis, R., & Carver, C. S. (1980). Self-focus and estimation of heart rate following physical exertion. *Bulletin of the Psychonomic Society*, **15**, 118–120.
- Gilman, M. B., & Wells, C. L. (1993). The use of heart rates to monitor exercise intensity in relation to metabolic variables. *International Journal of Sports Medicine*, **14**, 339–344.
- Goldstein, D. S., Ross, R. S., & Brady, J. V. (1977). Biofeedback heart rate training during exercise. *Biofeedback and Self-Regulation*, **2**, 107–125.
- Gonder-Frederick, L. A., & Cox, D. J. (1991). Symptom perception, symptom beliefs, and blood glucose discrimination in the self-treatment of insulin-dependent diabetes. In J. A. Skelton & R. T. Croyle (eds.), *Mental representation in health and illness* (pp. 220–246). New York: Springer-Verlag.
- Green, J. M., Michael, T., & Solomon, A. H. (1999). The validity of ratings of perceived exertion for cross-modal regulation of swimming intensity. *Journal of Sports Medicine and Physical Fitness*, **39**, 207–212.

- Gutmann, M. C., Squires, R. W., Pollock, M. L., Foster, C., & Anholm, J. (1981). Perceived exertion—heart rate relationship during exercise testing and training in cardiac patients. *Journal of Cardiac Rehabilitation*, **1**, 52–59.
- Hall, E. E., Ekkekakis, P., & Petruzzello, S. J. (2002). The affective beneficence of vigorous exercise revisited. *British Journal of Health Psychology*, **7**, 47–66.
- Hardy, C. J., & Rejeski, W. J. (1989). Not what, but how one feels: The measurement of affect during exercise. *Journal of Sport & Exercise Psychology*, **11**, 304–317.
- Hardy, C. S., Hall, E. G., & Prestholdt, P. H. (1986). The mediational role of social influence in the perception of exertion. *Journal of Sport Psychology*, **8**, 88–104.
- Hatfield, B. D., Spalding, T. W., Mahon, A. D., Slater, B. A., Brody, E. B., & Vaccaro, P. (1992). The effect of psychological strategies upon cardiorespiratory and muscular activity during treadmill running. *Medicine and Science in Sports and Exercise*, **24**, 218–225.
- Hetzler, R. K., Seip, R. L., Boutcher, S. H., Pierce, E., Snead, D., & Weltman, A. (1991). Effect of exercise modality on ratings of perceived exertion at various lactate concentrations. *Medicine and Science in Sports and Exercise*, **23**, 88–92.
- Hill, D. W., Cureton, K. J., Grisham, S. C., & Collins, M. A. (1987). Effect of training on the rating of perceived exertion at the ventilatory threshold. *European Journal of Applied Physiology*, **56**, 206–211.
- Hodes, R. L., Howland, E. W., Lightfoot, N., & Cleeland, C. S. (1990). The effects of distraction on responses to cold pressor pain. *Pain*, **41**, 109–114.
- Hollandsworth, J. G. (1979). Some thoughts on distance running as training in biofeedback. *Journal of Sport Behavior*, **2**, 71–82.
- Hollandsworth, J. G., & Jones, G. E. (1979). Perceptions of arousal and awareness of physiological responding prior to and after running 20 kilometers. *Journal of Sport Psychology*, **1**, 291–300.
- Jacobsen, S., & Johansen, O. (1974). An ergometer bicycle controlled by heart rate. *Medical and Biological Engineering*, **12**, 675–680.
- Johnston, D. W., & Lo, C. R. (1983). The effects of cardiovascular feedback and relaxation on angina pectoris. *Behavioural Psychotherapy*, **11**, 257–264.
- Johnston, D. W., Lo, C. R., Marie, G. V., & Van Jones, J. (1982). Self-control of inter-beat interval and pulse transit time at rest and during exercise: A preliminary report. *Acta Medica Scandinavica Supplementum*, **660**, 238–243.
- Jones, G. E. (1994). Perception of visceral sensations: A review of recent findings, methodologies, and future directions. In J. R. Jennings, P. K. Ackles, & M. G. H. Coles (eds.), *Advances in psychophysiology: A research annual* (vol. 5; pp. 55–191). London: Jessica Kingsley.
- Jones, G. E., & Hollandsworth, J. G. (1981). Heart rate discrimination before and after exercise-induced augmented cardiac activity. *Psychophysiology*, **18**, 252–257.
- Katch, V., Weltman, A., Sady, S., & Freedson, P. (1978). Validity of the relative percent concept for equating training intensity. *European Journal of Applied Physiology*, **39**, 219–227.
- Kawada, T., Sunagawa, G., Takaki, H., Shishido, T., Miyano, H., Miyashita, H., Sato, T., Sugimachi, M., & Sunagawa, K. (1999). Development of a servo-controller of heart rate using a treadmill. *Japanese Circulation Journal*, **63**, 945–950.
- Kinsman, R. A., & Weiser, P. C. (1976). Subjective symptomatology during work and fatigue. In E. Simonson & P. C. Weiser (eds.), *Psychological aspects and physiological correlates of work and fatigue* (pp. 336–405). Springfield, IL: Charles C. Thomas.
- Kinsman, R. A., Weiser, P. C., & Stamper, D. A. (1973). Multidimensional analysis of subjective symptomatology during prolonged strenuous exercise. *Ergonomics*, **16**, 211–226.
- Kirkcaldy, B. D., & Christen, J. (1981). An investigation into the effect of EMG frontalis biofeedback on physiological correlates of exercise. *International Journal of Sport Psychology*, **12**, 235–252.
- Kollenbaum, V. E. (1994). A clinical method for the assessment of interoception of cardiovascular strain in CHD patients. *Journal of Psychophysiology*, **8**, 121–130.



- Kollenbaum, V. E., Dahme, B., & Kirchner, G. (1996). "Interoception" of heart rate, blood pressure, and myocardial metabolism during ergometric work load in healthy young subjects. *Biological Psychology*, **42**, 183–197.
- Kosiek, R. M., Szymanski, L. M., Lox, C. L., Kelley, G., & MacFarlane, P. A. (1999). Self-regulation of exercise intensity in cardiac rehabilitation patients. *Sports Medicine Training and Rehabilitation*, **8**, 359–368.
- Laperriere, A. R., VanDercar, D. H., Shyu, L. Y., Ward, M. F., McCabe, P. M., Perry, A. C., Mosher, P. E., & Schneiderman, N. (1989). Microcomputer servo-controlled bicycle ergometer system for psychophysiological research. *Psychophysiology*, **26**, 201–207.
- Lazarus, R. S. (1975). A cognitively oriented psychologist looks at biofeedback. *American Psychologist*, **30**, 553–561.
- Lazarus, R. S. (1977). A cognitive analysis of biofeedback control. In G. E. Schwartz & J. Beatty (eds.), *Biofeedback: Theory and Research* (pp. 67–87). New York: Academic.
- Lazarus, R. S. (1991). Progress on a cognitive-motivational-relational theory of emotion. *American Psychologist*, **46**, 819–834.
- Lee, C. (1995). Comparing the incommensurable: Where science and politics collide. *Journal of Behavior Therapy and Experimental Psychiatry*, **26**, 259–263.
- Lee, I. M., Hsieh, C. C., & Paffenbarger, R. S. Jr. (1995). Exercise intensity and longevity in men: the Harvard Alumni Health Study. *Journal of the American Medical Association*, **273**, 1179–1184.
- Lee, J. Y., Jensen, B. E., Oberman, A., Fletcher, G. F., Fletcher, B. J., & Raczyński, J. M. (1996). Adherence in the Training Levels Comparison Trial. *Medicine and Science in Sports and Exercise*, **28**, 47–52.
- Lo, C. R., & Johnston, D. W. (1984a). Cardiovascular feedback during dynamic exercise. *Psychophysiology*, **21**, 199–206.
- Lo, C. R., & Johnston, D. W. (1984b). The self-control of the cardiovascular response to exercise using feedback of the product of interbeat interval and pulse transit time. *Psychosomatic Medicine*, **46**, 115–125.
- McAuley, E. (1994). Enhancing psychological health through physical activity. In H. A. Quinney, L. Gauvin, & A. E. T. Wall (eds.), *Toward active living: Proceedings of the international conference on physical activity, fitness, and health* (pp. 83–90). Champaign, IL: Human Kinetics.
- Montgomery, W. A., Jones, G. E., & Hollandsworth, J. G. (1984). The effects of physical fitness and exercise on cardiac awareness. *Biological Psychology*, **18**, 11–22.
- Morgan, W. P. (1989). Sport psychology in its own context: A recommendation for the future. In J. S. Skinner & C. B. Corbin (eds.), *Future directions in exercise and sport science research* (pp. 97–110). Champaign, IL: Human Kinetics.
- Morris, J. N. (1996). Exercise versus heart attack: questioning the consensus? *Research Quarterly for Exercise and Sport*, **67**, 216–220.
- National Institutes of Health (1996). NIH consensus development panel on physical activity and cardiovascular health: Physical activity and cardiovascular health. *Journal of the American Medical Association*, **276**, 241–246.
- Noble, B. J., & Robertson, R. J. (1996). *Perceived exertion*. Champaign, IL: Human Kinetics.
- Parfitt, G., & Eston, R. (1995). Changes in ratings of perceived exertion and psychological affect in the early stages of exercise. *Perceptual and Motor Skills*, **80**, 259–266.
- Parfitt, G., Eston, R., & Connolly, D. (1996). Psychological affect at different ratings of perceived exertion in high- and low-active women: A study using a production protocol. *Perceptual and Motor Skills*, **82**, 1035–1042.
- Parfitt, G., Markland, D., & Holmes, C. (1994). Responses to physical exertion in active and inactive males and females. *Journal of Sport & Exercise Psychology*, **16**, 178–186.
- Pennebaker, J. W., & Hoover, C. W. (1984). Visceral perception and visceral detection: Distinguishing methods and assumptions. *Biofeedback and Self-Regulation*, **9**, 339–352.

- Perski, A., & Engel, B. T. (1980). The role of behavioral conditioning in the cardiovascular adjustment to exercise. *Biofeedback and Self-Regulation*, **5**, 91–104.
- Perski, A., Tzankoff, S. P., & Engel, B. T. (1985). Central control of cardiovascular adjustments to exercise. *Journal of Applied Physiology*, **58**, 431–435.
- Petruzzello, S. J., Landers, D. M., & Salazar, W. (1991). Biofeedback and sport/exercise performance: Applications and limitations. *Behavior Therapy*, **22**, 379–392.
- Potteiger, J. A., & Evans, B. W. (1995). Using heart rate and ratings of perceived exertion to monitor intensity in runners. *Journal of Sports Medicine and Physical Fitness*, **35**, 181–186.
- Pratt, W. M., Siconolfi, S. F., Webster, L., Hayes, J. C., Mazzocca, A. D., & Harris, B. A. (1991). A comparison between computer-controlled and set work rate exercise based on target heart rate. *Aviation, Space, and Environmental Medicine*, **62**, 899–902.
- Purvis, J. W., & Cureton, K. J. (1981). Ratings of perceived exertion at the anaerobic threshold. *Ergonomics*, **24**, 295–300.
- Pyne, D. B., Boston, T., Martin, D. T., & Logan, A. (2000). Evaluation of the Lactate Pro blood lactate analyzer. *European Journal of Applied Physiology*, **82**, 112–116.
- Rejeski, W. J. (1981). The perception of exertion: A social psychophysiological integration. *Journal of Sport Psychology*, **4**, 305–320.
- Rejeski, W. J. (1985). Perceived exertion: An active or passive process. *Journal of Sport Psychology*, **7**, 371–378.
- Rejeski, W. J., & Ribisl, P. M. (1980). Expected task duration and perceived effort: An attributional analysis. *Journal of Sport Psychology*, **2**, 227–236.
- Rejeski, W. J., & Thompson, A. (1993). Historical and conceptual roots of exercise psychology. In P. Seraganian (ed.), *Exercise psychology: The influence of physical exercise on psychological processes* (pp. 3–35). New York: John Wiley.
- Robertson, R. J. (1982). Central signals of perceived exertion during dynamic exercise. *Medicine and Science in Sports and Exercise*, **14**, 390–396.
- Sada, K., Hamada, S., Yonezawa, Y., & Ninomiya, I. (1999). Self-biofeedback control of heart rate during exercise. *Japanese Journal of Physiology*, **49**, 275–281.
- Sallis, J. F., Haskell, W. L., Fortmann, S. P., Vranizan, K. M., Taylor, C. B., & Solomon, D. S. (1986). Predictors of adoption and maintenance of physical activity in a community sample. *Preventive Medicine*, **15**, 331–341.
- Sime, W. E. (1985). Physiological perception: The key to peak performance in athletic competition. In J. H. Sandweiss & S. L. Wolf (eds.), *Biofeedback and sports science* (pp. 33–62). New York: Plenum.
- Smutok, M. A., Skrinar, G. S., & Pandolf, K. B. (1980). Exercise intensity: Regulation by perceived exertion. *Archives of Physical Medicine and Rehabilitation*, **61**, 569–574.
- Talan, M. I., & Engel, B. T. (1986). Learned control of heart rate during dynamic exercise in nonhuman primates. *Journal of Applied Physiology*, **61**, 545–553.
- Thompson, D. L., & West, K. A. (1998). Ratings of perceived exertion to determine intensity during outdoor running. *Canadian Journal of Applied Physiology*, **23**, 56–65.
- United States Department of Health and Human Services (1996). *Physical activity and health: A report of the Surgeon General*. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion.
- United States Department of Health and Human Services. (2000). *Healthy people 2010*. Washington, DC: Author.
- United States National Center for Health Statistics (1999). *Healthy people 2000 review, 1998–1999*. Hyattsville, MD: Public Health Service.
- Weiser, P. C., Kinsman, R. A., & Stamper, D. A. (1973). Task-specific symptomatology changes resulting from prolonged submaximal bicycle riding. *Medicine and Science in Sports*, **5**, 79–85.

- Weltman, A., Seip, R. L., Snead, D., Weltman, J. Y., Haskvitz, E. M., Evans, W. S., Veldhuis, J. D., & Rogol, A. D. (1992). Exercise training at and above the lactate threshold in previously untrained women. *International Journal of Sports Medicine*, **13**, 257–263.
- Whaley, M. H., & Forsyth, G. (1990). The value of traditional intensity feedback for self-regulation of initial exercise training. *Journal of Cardiopulmonary Rehabilitation*, **10**, 98–106.
- Whaley, M. H., Woodall, M. T., Kaminsky, L. A., & Emmett, J. D. (1997). Reliability of perceived exertion during graded exercise testing in apparently healthy adults. *Journal of Cardiopulmonary Rehabilitation*, **17**, 37–42.
- Winett, R. A. (1998). Developing more effective health-behavior programs: Analyzing the epidemiological and biological bases for activity and exercise programs. *Applied & Preventive Psychology*, **7**, 209–224.
- Yamaji, K., Yokota, Y., & Shephard, R. J. (1992). A comparison of the perceived and the ECG measured heart rate during cycle ergometer, treadmill and stairmill exercise before and after perceived heart rate training. *Journal of Sports Medicine and Physical Fitness*, **32**, 271–281.
- Zaichkowsky, L. D., & Fuchs, C. Z. (1988). Biofeedback applications in exercise and athletic performance. *Exercise and Sport Sciences Reviews*, **16**, 381–421.