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Pleasure and displeasure from the body: Perspectives from exercise

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The affective changes associated with acute exercise have been studied extensively in exercise and health psychology, but not in affective psychology. This paper presents a summary of the relevant findings and a tentative theoretical model. According to this model, affective responses to exercise are jointly influenced by cognitive factors, such as physical self-efficacy, and interoceptive (e.g., muscular or respiratory) cues that reach the affective centres of the brain via subcortical routes. Furthermore, the balance between these two determinants is hypothesised to shift as a function of exercise intensity, with cognitive factors being dominant at low intensities and interoceptive cues gaining salience as intensity approaches the individual's functional limits and the maintenance of a physiological steady-state becomes impossible.

A large and continuously expanding research literature in the areas of exercise and health psychology and behavioural medicine shows that single bouts of exercise are commonly associated with what has been called a ''feel better'' response (Tuson & Sinyor, 1993; Yeung, 1996). Although the possible link between exercise-induced changes in the body and affect is an issue of great theoretical interest, this research has been almost exclusively descriptive, focusing on the practical implications for public health. Although the public health implications should not be overlooked, the absence of theory is striking and could hamper further progress (Ekkekakis & Petruzzello, 1999).

With the exception of a series of studies by Thayer and his co-workers, in which moderate exercise was shown to be one of the factors that contribute positively to the self-regulation of mood (Thayer, 1987a, b; Thayer, Peters, Takahashi, & Birkhead-Flight, 1993), the exercise-associated ''feel better'' phenomenon has received little attention in other areas of psychology. In the few studies that involved exercise treatments, exercise was assumed to produce a state of high arousal, devoid of any form of pleasure or displeasure, essentially

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serving as an analogue to the injections of epinephrine in Schachter's experiments (e.g., Anderson, Deuser, & DeNeve, 1995; Isen, Daubman, & Nowicki, 1987; Sinclair, Hoffman, Mark, Martin, & Pickering, 1994; Zillman & Bryant, 1974; Zillman, Katcher, & Milavsky, 1972).

In general, there are conflicting assumptions about the relationship between exercise and affect. One of the goals of this paper is to show that some of these assumptions are contradicted by empirical evidence and all tend to be monolithic, not recognising that the relationship is in fact multifaceted and dynamic. Another goal is to highlight that exercise can serve as a useful model for the investigation of one of the most controversial components of many theories of affect, namely the role of bodily input. To accomplish these goals, this paper will provide (a) definitions of the main terms that are used, (b) a note on measurement issues, (c) a review of empirical findings on the exercise-affect relationship showing that at least five distinct phenomena may be involved, and (d) an outline of a new ''dual-mode'' conceptual model for this relationship, accompanied by a synopsis of preliminary supporting evidence.

Distinguishing basic affect from emotions

The literature on the exercise-affect relationship has not been immune to problems of inconsistent or inappropriate use of terminology. It is, therefore, imperative to define the main terms used in this paper.

Emotion and *affect* are viewed here as occupying different levels along an evolutionary continuum (also see Ekkekakis & Petruzzello, 2000). The simplest and most phylogenetically and ontogenetically primitive response is *basic affect*. This term refers to the intrapersonal or experiential core of all valenced (i.e., positive or negative, pleasant or unpleasant) responses, including, but not limited to, emotions and moods. The concept is similar to what Russell and Feldman Barrett (1999) called *core affect*. Affect is described as ''basic'' or ''core'' because it is considered an ''irreducible'' (Frijda, 1993, p. 383) or the ''most elementary'' (Russell & Feldman Barrett, 1999, p. 806) component, the nucleus or essential ingredient of all the phenomena that make up the global affective domain (i.e., the broad domain that encompasses basic affect, emotions, moods, and other related phenomena). In the same sense, other authors have characterised affect as a ''broader'' (Ortony, Clore, & Foss, 1987, p. 343) or the ''most general'' of the concepts in this domain (Batson, Shaw, & Oleson, 1992, p. 298). Along similar lines, I follow Scherer (1984) in using *affective states* as a ''generic term'' (p. 298) that refers to all varieties of states that contain the ingredient of basic affect. Importantly, although basic affect (such as pleasure or displeasure, tension or relaxation, sluggishness or excitement, etc.) can exist as a component of emotions, there can also be basic affective responses to specific stimuli that occur independently of emotions. As an example from the context of exercise, when an individual reports feeling ''exhilarated'', it is possible that this sense of exhilaration is a component of an emotion (e.g., pride for having completed a challenging bout of exercise) or just that—pure exhilaration.

As alluded to in the previous paragraph, *emotions* are considered here to be more complex phenomena compared to basic affect (Ekkekakis & Petruzzello, 2000). In addition to their basic affective core, emotions may also comprise other components, such as attention directed toward the eliciting stimulus, a cognitive appraisal of the meaning of that stimulus for the survival and well-being of the individual, behavioural expressions or action tendencies, coping responses, a multitude of physiological changes, etc. Emphasis here is placed specifically on the process of *cognitive appraisal* as a *necessary* antecedent of emotions (Lazarus, 1991; Ortony et al., 1987). The term *cognitive appraisal* refers to an inferential process by which information from the internal or external environment is *evaluated* regarding its potential *meaning* for the survival, the well-being, and the goals of the individual (Lazarus, 1991). In agreement with Lazarus (1982), I do not assume that cognition in the context of emotion-antecedent appraisals implies ''anything about deliberate reflection, rationality, or awareness'' (p. 1022). The distinction between rapid, automatic, unreflective, and unconscious appraisal on the one hand and slow, deliberate, reflective, and conscious on the other is not pertinent to this analysis. Finally, as used here, the term refers only to a subset of the phenomena typically subsumed under the general rubric of *emotion* by many authors in neuroscience (e.g., Damasio, 1995; LeDoux, 2000a).

Measurement issues

As a reflection of the confusion regarding the conceptual distinctions between affective phenomena, the measurement and operationalisation of affective responses to exercise has become a major source of controversy over the years (Ekkekakis & Petruzzello, 1999, 2000). In most studies, the selection of measures was not guided by which construct was the genuine target of investigation, but rather by what measures were available or popular for use with non-clinical samples, regardless of their exact content and without any prior psychometric evaluations in the context of exercise. After three decades of research, the present situation is strikingly similar to that in the area of research dealing with the affective changes associated with drugs, as described by Russell (1989). Most studies report changes in several distinct affective states, but it remains impossible to integrate this information and, thus, identify the nature of the most salient changes or pinpoint the effects of moderating variables.

Several reviews and empirical studies published in the 1990s began to call some of the traditional measurement practices into question. Some of the most oft-cited problems were the overemphasis on negative states and the floor effects resulting from measuring negative emotions, such as state anxiety, in studies that did not involve trait-anxious participants or the induction of state anxiety. From a theoretical standpoint, the most important issue that surfaced was that certain measures were shown to confound exercise-induced changes in perceived activation with emotional changes. For example, items from the state anxiety scale of the State Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, & Lushene, 1970) referring to cognitive antecedents of anxiety, such as worry, show decreases with exercise, whereas items that reflect perceived activation show increases during and decreases after vigorous exercise, mirroring changes in autonomic activation and self-reports of perceived activation (Ekkekakis, Hall, & Petruzzello, 1999a; Rejeski, Hardy, & Shaw, 1991).

As a way of addressing these problems, some researchers turned to the development of exercise-specific measures (Gauvin & Rejeski, 1993; McAuley & Courneya, 1994). This approach consisted of asking young, healthy, and physically active respondents to indicate whether they experience various affective states when they exercise and grouping the states found to be ''relevant'' to exercise into scales. However, this approach is also problematic, since (a) it is atheoretical, (b) it was developed in the absence of evidence that the affective domain is uniquely transformed in the context of exercise, (c) retrospective reports from a single demographic group have limited generalisability, and (d) there is a potential for bias when measures that were tailored to reflect only responses to exercise are used to assess responses to sedentary comparison or control conditions (Ekkekakis & Petruzzello, 2001a,b).

The measurement approach used in the research that our group has conducted is different and is based on a dimensional model of affect, namely the circumplex (Russell, 1978, 1980; see Larsen & Diener, 1992 for a critical review; see Figures 1 and 2 for examples). The reasons for selecting this model were that (a) it targets basic affect, the simplest and broadest concept in the affective hierarchy, (b) as a dimensional model, it offers unparalleled parsimony, allowing the integration of findings within the global affective space, (c) it is domain-general, and (d) it is based on a strong theoretical and empirical foundation (Ekkekakis & Petruzzello, 2000, 2002). Typically, both the ''unrotated'' (i.e., affective valence and activation) and the 45° rotated dimensions (extending from high-activation pleasant to low-activation unpleasant affect and from high-activation unpleasant to low-activation pleasant affect, respectively) are assessed. Valence and activation are commonly assessed by two single-item scales, the Feeling Scale (FS; Hardy & Rejeski, 1989) and the Felt Arousal Scale (FAS) of the Telic State Measure (Svebak & Murgatroyd, 1985), respectively. The rotated dimensions are assessed by the Activation Deactivation Adjective Check List (AD ACL; Thayer, 1989). Specifically, the *Energetic Arousal* scale of the AD ACL (ranging from *Energy* to *Tiredness*) is used to tap the dimension that extends from high-activation pleasant to low-activation unpleasant affect and the *Tense Arousal* scale (ranging from *Tension* to *Calmness*) is used to tap the dimension that extends from high-activation unpleasant to low-activation pleasant affect (Yik, Russell, & Feldman Barrett, 1999).

Targeting basic affect and assessing it from a dimensional perspective has several advantages for research in the context of exercise (Ekkekakis & Petruzzello, 2002), but there are still some challenges. One such issue is of particular interest here given its relevance to the subsequent discussion and its implications for the controversial issue of the relationship (i.e., independence vs. bipolarity) between positive and negative affect. In exercise, especially among trained and physically fit individuals, a commonly used expression is that vigorous exercise ''hurts so good''. Although this may be seen as supporting the notion of independence, an alternative interpretation is that these apparently conflicting responses originate from different levels of the affective hierarchy. The ''hurt'' may reflect the inherent unpleasantness of the bodily sensations that accompany strenuous physical effort (i.e., basic affect), whereas the ''good'' feeling may reflect a sense of pride (i.e., an emotion) sparked by the thought that, by exercising, one is doing something good for his or her health, fitness, or physical appearance. For example, in a study involving middle-aged women, participation in a maximal treadmill test resulted in increases in both fatigue and self-esteem (Pronk, Crouse, & Rohack, 1995). The distinction between responses that may originate from different levels of the affective hierarchy is extremely important from a theoretical standpoint, but still outside the reach of available measures.

Affective responses to exercise: One phenomenon or many?

Despite the fact that most writings on the relationship between exercise and affect give the impression that we are dealing with a unitary phenomenon (i.e., ''exercise makes people feel better''), there is evidence that the relationship is in fact considerably more complex. Based on the nature of affective changes, the inter-individual variability of changes, and the patterns of relationships with relevant variables, at least five distinct phenomena can be identified.

First, there are positive affective responses during and for a short time following bouts of physical activity of mild intensity and short duration. This has been a relatively controversial finding. Based on a few earlier studies showing that low-intensity and short-duration exercise had no significant effects on state anxiety, some authors argued that such ''small doses'' of activity are not sufficient to produce significant affective changes and, instead, speculated that exercise intensity and duration should exceed certain relatively vigorous thresholds before significant changes can occur (Dishman, 1986; Raglin & Morgan, 1985). However, studies that have examined variables other than state anxiety have produced different results. For example, research using the AD

ACL (Thayer, 1989) has shown that walks at a self-chosen pace lasting for as little as 4 to 10 min were associated with increases in Energy (Thayer, 1987a,b; Thayer et al., 1993) and decreases in Tension and Tiredness (Saklofske, Blomme, & Kelly, 1992; Thayer, 1987a; Thayer et al., 1993). In a recent series of studies, Ekkekakis, Hall, Van Landuyt, and Petruzzello (2000) found that short (10 to 15 min) self-paced walks were consistently associated with increased activation and improved valence. Post-walk recovery for 10 to 15 min was associated with a return to a low-activation pleasant state (see Figure 1). This pattern was robust across different self-report measures of the circumplex dimensions, across ecological settings (outdoors and in the laboratory), across two walks on different days, and across four samples.

Although the pattern of responses appears to be reliable, the mechanisms underlying the positive responses to low-intensity, short-duration exercise have received virtually no research attention and remain elusive. It is noteworthy that in healthy, normally ambulatory adults, the intensity of physical effort involved is very low (15–22% of age-predicted maximal heart rate reserve in the studies by Ekkekakis et al., 2000). At this level of intensity, the afferent signals from peripheral physiology are weak and perceived exertion on Borg's (1998) scale is

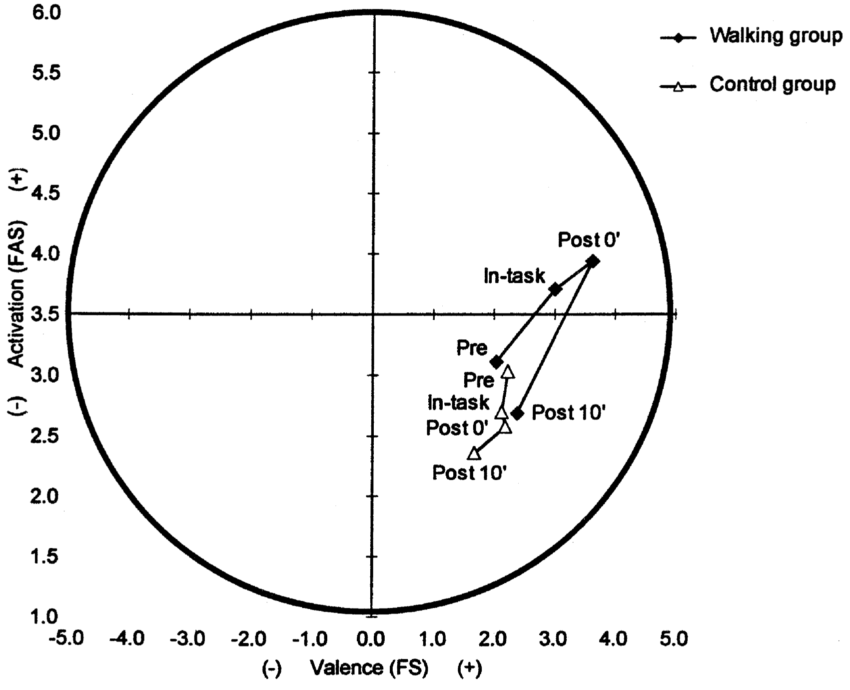

Figure 1. Affective responses to a 15-min walk on a treadmill at a self-selected intensity and a 10-min post-walk recovery period. (Data from Ekkekakis et al., 2000.)

rated as ''very light'' or ''fairly light''. This raises the possibility, as suggested by an earlier hypothesis (Morgan, 1985), that the positive changes occur not because of the exercise stimulus *per se* but rather because exercise provides a distraction from daily stressors. This hypothesis was prompted by findings that exercise led to decreases in state anxiety that were comparable to those following periods of quiet rest and meditation (Bahrke & Morgan, 1978). However, in the studies by Ekkekakis et al., walking led to high-activation pleasant affect, whereas periods of rest led to decreased activation with little change in valence. Therefore, the ''distraction'' hypothesis does not seem tenable. It is also noteworthy that low-intensity, short-duration exercise performed in noncompetitive settings (such as taking a short walk for recreation) is generally not perceived as physically challenging in disease- and pain-free individuals. Thus, variables such as self-efficacy that have been found to be related to affective responses to more challenging types of exercise have not been shown to be related to affective responses to low and moderate-intensity exercise (e.g., Treasure & Newbery, 1998, but see McAuley, Blissmer, Katula, & Duncan, 2000, for an exception in a study of older and previously sedentary adults).

One possibility that remains in the realm of speculation is that the positive affective responses to low-intensity, short-duration exercise reflect a reward mechanism, part of a biological system that has evolved to maintain a healthy balance between energy intake and expenditure (similar to mechanisms underlying pleasant and unpleasant responses to taste or thermal sensations; Cabanac, 1971, 1979, 1995). Rowland (1998) has discussed several indications from animal and human studies that such a system (creatively named ''activity-stat'') may exist. If this is true, it is possible that the tendency to ''go for a walk'' is partly motivated by the subconscious need to expend energy and that the positive affective changes associated with such activities are the manifestations of a mechanism that has evolved to reward and, thus, promote this behaviour. After all, although the physiological responses to this level of activity are minor, this information does reach the (subcortical) areas of the brain responsible for internal regulation (Craig, 1996). The problem is that the links between exercise, energy regulation, and affect will likely remain speculative, as direct evidence is very difficult to obtain in humans.

Second, affective responses during moderately vigorous exercise are characterised by marked inter-individual variability, with some individuals reporting positive and some reporting negative changes. The traditional assumption in exercise science has been that moderately vigorous exercise provides an optimal stimulus for positive affective change (Ojanen, 1994; Raglin & Morgan, 1985). Thayer (1989) has also described the amount of exercise that is likely to lead to increases in Energetic Arousal as ''moderate''. One problem with these suggestions is that the amount of exercise described as *moderate* has not been specified. The percentages of maximal capacity that have been assumed to provide the ''optimal'' dose (e.g., 60–70% of maximal aerobic capacity; Dishman, 1986; Raglin & Morgan, 1985) are essentially arbitrary, as they are not supported by conceptual reasoning or empirical evidence. A second problem is that these suggestions are based on examinations of affective change from pre- to various time points post-exercise, which are typically positive, although evidence from studies examining responses during exercise have shown a much more diverse pattern (Ekkekakis & Petruzzello, 1999).

In general, although the role of individual and situational variability is not entirely discounted, there has been a tendency to assume that the relationship between exercise intensity and affective responses is unitary. Therefore, it is often assumed that ''moderate'' exercise will produce positive affective responses in all or most individuals. For example, Morgan (1997) asserted that, although individual physiological and psychological profiles should be taken into account, it may still ''be possible to defend a single exercise prescription for all individuals (e.g., 70% [of maximal aerobic capacity])'' (p. 11). Based on this assumption, the majority of applied research to date has employed exercise stimuli within the ''moderate'' range, namely between 60% and 70% of maximal capacity and for 20–30 min. In a study designed to examine whether an exercise bout in this range (i.e., 30 min on a stationary cycle at 60% of estimated maximal aerobic capacity) leads to the assumed universally positive affective changes, Van Landuyt, Ekkekakis, Hall, and Petruzzello (2000) found that, although 97% of the participants reported either an increase or no change in activation during exercise, 44% reported a progressive improvement in valence whereas 41% reported a progressive decline. As a result of these divergent trends, the average valence responses appeared unchanged during exercise. Interestingly, this variability during exercise was followed by a convergence toward improvement after exercise. Thus, it seems that, contrary to the assumption of universality, valence responses during exercise can vary considerably between individuals.

The challenge is to identify the sources of this variability. Although the size of the relevant literature remains limited, a number of variables, primarily from social-cognitive theories, have been shown to be related to affective responses to moderate exercise. These variables include attributions, goal orientations, and others, but the one that has been studied most extensively and has been shown to be consistently associated with affective responses in a variety of samples is self-efficacy (e.g., McAuley & Courneya, 1992; McAuley, Talbot, & Martinez, 1999; Treasure & Newbery, 1998).

An important question that is receiving increasing attention is whether the variance in affective responses accounted for by self-efficacy changes as a function of exercise intensity. This question is particularly relevant to affective responses associated with moderate exercise, because it has been suggested that self-efficacy becomes a salient moderator of affect when the intensity of exercise presents an appreciable challenge (e.g., 70% of maximal heart rate;

McAuley & Courneya, 1992), but, if the intensity is too high, its influence is weakened because ‘‘physiological cues ... override cognitive processing’’ (McAuley et al., 2000, p. 352). However, the data on this issue are inconsistent. Treasure and Newbery (1998) showed that self-efficacy was related to physical exhaustion when the intensity was 70–75% but not when it was 45–50% of heart rate reserve. Conversely, Tate, Petruzzello, & Lox (1995) found that self-efficacy was related to scores on the Tense Arousal scale of the AD ACL during exercise performed at 55%, but not at 70% of maximal aerobic capacity. Finally, in a study of older adults, McAuley et al. (2000) found that changes in self-efficacy were unrelated to changes in affect in a moderate exercise intensity condition, but were related to changes in affect in a light and in a maximal exercise intensity condition. As in much of this research, the inconsistency in the findings may be due to differences in the age and physical condition of the participants, the measures of affect, and the exercise loads. To examine the relationship between self-efficacy and affective valence across a greater range of intensities, Ekkekakis, Hall, and Petruzzello (1999b) used an exercise protocol in which the speed and grade of a treadmill were increased every minute, from a slow jog to the point of volitional exhaustion. Consistent with the hypothesis that the relationship should be stronger at moderate levels of intensity, the results showed significant positive correlations between self-efficacy and affective valence near the middle of the range, but not in the early stages or at the point of volitional exhaustion.

A noticeable void in this literature is the absence of studies on the role of personality. This is partly due to the fact that the standard measures of relevant personality traits (i.e., extraversion, sensation seeking, behavioural activation/inhibition, etc.) emphasise social behaviour over responses to somatosensory stimuli, making it difficult to find significant relationships with affective responses to exercise. Nevertheless, individual differences are likely to play an important role. For example, in a preliminary series of studies on the role of exercise-specific sensory modulation, Ekkekakis, Hall, and Petruzzello (2001) found that preference for and tolerance of exercise intensity accounted for approximately 25% and 20%, respectively, of the variance in valence during moderate exercise. In general, affective responses to moderate exercise can vary considerably between individuals. Social-cognitive variables and some individual differences may account for substantial portions of this variability.

Third, responses immediately following moderately vigorous exercise are almost uniformly positive, regardless of whether the responses during exercise were positive or negative. The robustness of this post-exercise positive change is remarkable. It is a phenomenon that seems to transcend modes of exercise, exercise environments, types of participants, and measures of affect. It quickly eradicates any divergent trends that might have occurred during exercise (Ekkekakis & Petruzzello, 1999). Although compared to assessments made during exercise, activation begins to drop, average valence ratings improve. This improvement is more dramatic among those who report a deterioration during exercise, but it is noticeable even for those who report an improvement during exercise (Ekkekakis et al., 1999a). Compared to pre-exercise, the average post-exercise state is characterised by higher (although gradually decreasing) activation and improved valence. During post-exercise recovery, this state is progressively transformed into a low-activation pleasant state.

For those individuals who report a positive change immediately post-exercise, following a negative trend during exercise, Solomon's (1980, 1991) opponent process model (to be discussed shortly) may provide a possible explanation. On the other hand, for those individuals with already positive trends during exercise, the continued positive changes in valence after exercise may be a reflection of at least some of the same mechanisms that produced the positive changes during exercise. The overlap, however, is unlikely to be complete because the post-exercise positive changes are accompanied by decreases in activation, whereas the during-exercise positive changes are accompanied by increases. No research exists on this issue.

Fourth, affective responses during strenuous exercise unify into a negative trend as the intensity of exercise approaches each individual's functional limits. In several studies in which the intensity of exercise was gradually increased to levels that approached the participants' physical limits, valence ratings showed a progressive decline with each increase in intensity (Acevedo, Rinehardt, & Kraemer, 1994; Hardy & Rejeski, 1989; Parfitt & Eston, 1995; Parfitt, Eston, & Connolly, 1996; Parfitt, Markland, & Holmes, 1994). Furthermore, as exercise intensity increased, the negative correlations between valence and various indices of metabolic strain (heart rate, ventilation, respiratory rate, oxygen consumption, blood lactate) increased in magnitude (Acevedo et al., 1994; Hardy & Rejeski, 1989), suggesting an increasingly stronger link between valence and interoceptive afferents.

In two studies, we examined whether the negative shift in affective valence is specifically linked to an important metabolic event, namely the transition from aerobic to anaerobic metabolism. This is perhaps the single most important landmark in the entire range of exercise intensity from an adaptational standpoint. This is because, although the energy resources that are available for aerobic metabolism are vast, the resources that are available for anaerobic metabolism are limited. As a result, one can continue to exercise for only a brief period of time at this level of intensity before the energy resources are depleted and exhaustion sets in. The determination of the level of exercise intensity that corresponds to the transition from aerobic to anaerobic metabolism is done by continuously collecting the expired gases, analysing them for oxygen and carbon dioxide, and determining the so-called ventilatory threshold, the point at which there is a systematic increase in the ventilatory equivalent of oxygen without a corresponding increase in the ventilatory equivalent of carbon dioxide. In the first study (Hall, Ekkekakis, & Petruzzello, 2002), we examined minute-by-minute ratings of valence and activation as exercise intensity (the speed and incline of a treadmill) was gradually increased until each participant reached the point of volitional exhaustion. The results showed that, during the early stages, affective change was characterized primarily by an increase in activation, with little change in valence. After the transition to anaerobic metabolism, however, the continued increase in activation was coupled with a substantial shift toward negative valence (see Figure 2). Furthermore, an examination of the inter-individual variability in minute-to-minute changes in valence showed that, despite large variability during the early stages, starting with the minute following the ventilatory threshold and until exhaustion, the valence ratings of most participants exhibited a relatively homogeneous pattern of decline. Similar results were obtained in a second study (Ekkekakis, Hall, & Petruzzello, in

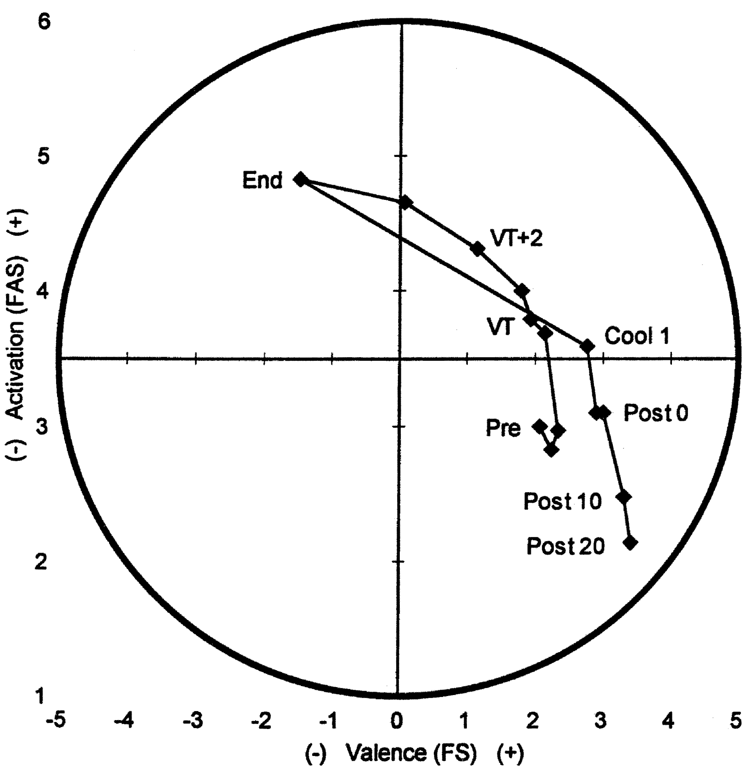

Figure 2. Affective responses to a graded treadmill test performed until volitional exhaustion and a 20-min recovery period. (*Note:* VT: ventilatory threshold; VT+2 min 2 after the VT; Cool 1: min 1 of the cool-down). (Data from Hall et al., 2002.)

press), in which the participants ran at a constant pace for 15 min at three intensities, one below, one at, and one above the ventilatory threshold. Again, with increasing intensity, there were larger increases in activation and declines in valence. Particularly during the run above the ventilatory threshold, the pattern of decline in valence fit a quadratic trend, indicating a more rapid rate of decline over time compared to the intensities below and at the ventilatory threshold. Analyses of inter-individual variability in changes in valence over the course of the runs also showed less variability above the ventilatory threshold.

Furthermore, in both studies, physiological variables showed strong negative relationships with ratings of affective valence at intensities above the ventilatory threshold (these results are reported in Ekkekakis et al., 1999b, Ekkekakis, Hall, & Petruzello, 2002). During the incremental treadmill test, the respiratory exchange ratio (the ratio of carbon dioxide produced to oxygen consumed) accounted for less than 10% of the variance in valence below, but for approximately 30–50% above the ventilatory threshold and until exhaustion. During constant-pace exercise (during which ventilatory data were not collected), above the ventilatory threshold (when there was no physiological steady state), the correlation between valence and the percentage of maximal heart rate was gradually strengthened from .08, to −.45, whereas no relationship was found during the runs below and at the ventilatory threshold. Therefore, it seems that strenuous exercise, particularly at an intensity that exceeds the ability of the metabolic system to supply energy through purely aerobic means, leads to declines in affective valence that exhibit limited inter-individual variability. Furthermore, a substantial portion of the variance in valence ratings at this level of intensity is accounted for by physiological variables.

Fifth, there is a homogeneous positive shift in affective valence immediately following strenuous exercise. In Hall et al. (2002), affective valence was assessed at the point of volitional exhaustion and one and two minutes later, as the participants were cooling-down by walking on the treadmill at a slow pace. Within just the first minute of the cool-down, affective valence had returned to the level it was before and during the first few minutes of the incremental exercise protocol. Furthermore, the patterns of inter-individual variability of changes in valence for all the stages of the test showed that the dramatic improvement that followed the termination of the test was the least variable response, even more homogeneous than the negative change during the last minute before volitional exhaustion.

The mechanisms that underlie the instantaneous improvement in affective valence that follows the negative response to exhaustive exercise are, again, unclear. Descriptively, the pattern of responses resembles what Solomon (1991) described as the *affective contrast* phenomenon. He proposed that this pattern of responses might be driven by an affective opponent process (Solomon 1980, 1991; Solomon & Corbit, 1974). Specifically, Solomon proposed that, in response to certain stimuli, including exercise that exceeds a critical threshold of intensity, affective responses are the algebraic sum of two processes that carry opposite valence signs. He attributed this function to a hypothetical affect summator, which determines the quality of the affect experienced at any given moment. Therefore, although the affect may be co-determined by two distinct processes, the experience is unitary. In this regard, Solomon's notion is consistent with the philosophical view that, although conscious experience may be determined by multiple spatially distributed and specialised assemblies of neurons in the brain, consciousness itself is unitary at each moment in time (e.g., Greenfield, 1995). According to Solomon, the primary process, the so-called *a*-process, is an unconditioned response aroused by the onset of the stimulus. It closely tracks the intensity of the eliciting stimulus and disappears shortly after the termination of that stimulus. The appearance of the *a*-process, after a short delay, leads to the elicitation of a secondary process, the so-called *b*-process, which has the opposite valence. Not only is the *b*-process slower to appear than the *a*-process, but it also has a slower build-up and a slower decay. As a result, the effects of the *b*-process persist for a period of time following the termination of the eliciting stimulus. Thus, what Solomon (1991) called the ''standard pattern of affective dynamics'' in response to a relevant stimulus, such as exercise, is characterised by two consecutive states. State A is the period of time during which the eliciting stimulus is present and affect is the result of the algebraic summation of the *a*- and *b*-processes. State B is the period that follows the cessation of the eliciting stimulus, during which affect depends solely on the *b*-process, since the *a*-process ends almost immediately after the removal of the stimulus. The strength of the *b*-process is hypothesised to increase with repeated exposures to the stimulus. Solomon has argued that, in the case of exercise, the *a*-process is charged with negative affective valence, whereas the *b*-process is charged with positive valence. Thus, although during exercise (particularly in physically unconditioned individuals participating in exercise for the first few times), the responses may be negative, following exercise, the response is positive.

Although the predictions of the opponent process model are consistent with the patterns of affective responses to exercise typically reported in the literature, the possible substrates of the *a*- and *b*-processes have not been explored systematically. Given that, according to Solomon (1980, 1991), the *a*-process is activated only in response to stimuli that exceed a critical level of intensity, then tracks the intensity of the eliciting stimulus, and finally disappears upon the termination of that stimulus, it is possible that what drives the *a*-process in the context of exercise are the interoceptive signals that carry information from receptors stimulated by the chemical, circulatory, mechanical, and other peripheral physiological changes that take place during strenuous exercise. As noted earlier, the declines in affective valence with increasing intensity, particularly following the transition from aerobic to anaerobic metabolism, are related to physiological variables (Acevedo et al., 1994; Ekkekakis et al., 2002; Hardy & Rejeski, 1989). On the other hand, Solomon (1980) speculated that the *b*-process might be driven by the endogenous opiate system. The hypothesis that the so-called ''exercise high'' or ''runner's high'' is linked to the known increases in peripheral opiates during vigorous exercise has been frequently cited in the popular press, but research evidence is mixed (Hoffmann, 1997). What may hold some promise, however, is a hypothesis by Hatfield and Landers (1987) that *central* opiates in particular may be linked to the positive post-exercise affective changes through their role in returning peripheral physiological activity toward baseline (i.e., reducing heart rate and blood pressure, slowing respiration, etc.; Vaccarino & Kastin, 2000) and, thus, alleviating the symptoms of exertion. Opiate levels in several brain regions have been reported to increase in response to acute exercise, including areas involved in cardiovascular and respiratory regulation. Decreases in heart rate, blood pressure, and respiratory activity induced by opiate agonists are reversed by naloxone, an opiate antagonist that crosses the blood-brain barrier. However, the hypothesis by Hatfield and Landers has yet to be tested directly, as most relevant studies have concentrated instead on whether opiates are related to changes from pre- to post-exercise rather than immediately following strenuous exercise.

A synthesis and a proposed dual-mode conceptual model

As shown in the foregoing review, the affective responses associated with physical exercise constitute a complex and multifaceted phenomenon. There are pleasant and unpleasant responses, periods of low and high activation, patterns of individual variability and homogeneity, and multiple correlates whose strength of association with affective responses varies. Integrating this information into a conceptual model is a challenging task which is made more difficult by a number of factors, including the relatively small number of studies that have gone beyond mere description to the test of specific theory-driven hypotheses, the costly and laborious nature of metabolic assessments that limit sample sizes, and the inability to benefit from modern brain imaging methods due to the susceptibility of this technology to movement artifacts. At present, most of the information on the possible moderators of the exercise-affect relationship comes from correlational research and most of the information on the brain structures involved comes from animal studies or from research with somatic stimuli other than exercise (e.g., pain, visceroception). Although this situation makes speculation inevitable, the potential benefits from formulating even a tentative conceptual model make this effort worthwhile.

The first step in attempting to understand the substrates of affective responses to exercise is to examine exercise itself from an adaptational standpoint. As noted in the review, the intensity of exercise plays a critical role in influencing both the valence of the affective responses and the nature of their primary correlates. Analyses of the metabolic responses across the entire range of exercise intensity reveal three distinct domains of intensity (Gaesser & Poole, 1996). The first domain encompasses the lower range of intensities, in which an adequate supply of energy can be produced through aerobic metabolism. In this range, a physiological steady-state can be maintained for a long time and there is no accumulation of lactate (an acid by-product of the metabolism of glucose). The second domain begins at the point at which the ability of the metabolic system to provide an adequate supply of energy through aerobic means is exceeded and the process must be supplemented by anaerobic metabolism. In this domain, lactate begins to appear at a rate that exceeds the rate of removal, leading to an accumulation of lactate known as the ‘‘lactate threshold’’. However, if the rate of accumulation is not too rapid, over time there may be a new stabilisation of lactate, but this time at increased levels of concentration. The intensity that corresponds to this ‘‘maximal lactate steady-state’’ is the upper limit of this domain. Another important change in this domain is that the rate of oxygen uptake cannot be stabilised and, instead, there is a gradual increase in oxygen cost per unit of work. In this range of intensity, there is a potential threat to homeostasis since the maintenance of a physiological steady-state is no longer possible and the production of energy depends in part upon the limited resources available for anaerobic metabolism. The final domain of intensity extends from the higher level at which lactate can be stabilised to the point of maximal exercise capacity. In this range, neither oxygen uptake nor lactate can be stabilised. Both rise continuously until exercise is terminated due to exhaustion.

The adaptational implications of this typology are fairly clear. In the low range of intensity, activity can be continued for a long time while in a physiological steady-state. This situation poses no threat to homeostasis and the physiological adjustments that occur remain largely outside awareness. Then, there is a range of intensity in which the maintenance of a steady-state is threatened. In this range, the amount and intensity of interoceptive information increases exponentially, as the accumulating lactate stimulates free nerve endings, respiration becomes quicker and deeper, and additional (nonoxidative) muscle fibres are recruited disrupting coordination patterns. Since this situation presents a potential challenge, good adaptational sense dictates that the possibility of a critical homeostatic perturbation should enter consciousness. As several authors have noted, affect provides the primary means by which information about critical disruptions of homeostasis enters consciousness (Cabanac, 1995; Damasio, 1995, 1999, 2000; Panksepp, 1998a,b; Schulze, 1995). Finally, above the maximal lactate steady-state, the energy supply system is overwhelmed and the maintenance of a steady-state is impossible. At this point, if the intensity of the activity is not reduced or the activity is not stopped, the available energy stores will soon be depleted and the muscles will go into rigor. What prevents this from happening is a strong and unambiguously negative affective ‘‘message’’ from the body.

The second step in attempting to gain insight into the mechanisms underlying the affective responses to exercise is to examine their correlates. Although research is still at an early stage, it appears that there are two main classes of correlates. On the one hand, there are several cognitive constructs (of which self-efficacy is the one that has been studied most extensively). On the other, there are physiological variables that reflect the level of metabolic strain. The results show that the variables in the latter category exhibit increasingly negative relationships with valence across increasing levels of exercise intensity (Acevedo et al., 1994; Ekkekakis et al., 1999b; Hardy & Rejeski, 1989). The information on how the relationship between the cognitive variables and affective valence changes as a function of exercise intensity is more scarce and less clear. The studies that have focused on self-efficacy have yielded conflicting results (McAuley et al., 2000; Tate et al., 1995; Treasure & Newbery, 1998). However, in the only study that took into account the balance between aerobic and anaerobic metabolism, the relationship between self-efficacy and valence was shown to be weak below the aerobic-anaerobic transition and at the point of exhaustion, but stronger around the point of transition, when the challenge to participants was presumably appreciable but not overwhelming (Ekkekakis et al., 1999b).

A crucial question is whether and how the cognitive and peripheral physiological influences on affect interact across the domains of exercise intensity. At this step, examining the structure of the brain mechanisms involved in the processing interoceptive information and the generation of affective responses can provide valuable insight. As is the case with the mechanisms involved in the processing of other types of somatosensory stimuli, afferent signals associated with exercise, such as signals from chemoreceptors, mechanoreceptors, articular nociceptors, thermoreceptors, baroreceptors, and various visceroceptors in the heart, lungs, and internal organs, reach areas with an increasingly complex network of connections as they ascend from the spinal cord to the cerebral cortex. This hierarchical organisation is assumed to be the result of an evolutionary process and to serve an adaptive function (Berntson, Boysen, & Cacioppo, 1993; Berntson & Cacioppo, 2000). Although adaptational problems could be solved by the complex and polysynaptic higher processing levels, those problems that have remained invariant and had to be solved reliably during the evolutionary history of the human species can also be solved by simpler, oligosynaptic, lower processing levels. In fact, solving such invariant adaptational problems through simpler mechanisms may not only represent a more efficient use of limited resources, but may also offer a considerable adaptational advantage. Oligosynaptic mechanisms may lack response flexibility but are fast and reliable (Berntson & Cacioppo, 2000; Griffiths, 1990). There are situations in which rigid, obligatory responses are preferable to responses from systems that could enter a multitude of factors into the equation, some of which may be impertinent or downright maladaptive. The wisdom of the hierarchical design is that it can allow the priority in the control of behaviour to shift between the higher and lower processing levels to fit varied adaptational needs (Berntson & Cacioppo, 2000).

LeDoux (1986, 1989, 1995, 1996, 2000a,b) has proposed a model of affective responses that is consistent with the notion of shifting control between higher and lower levels of the brain. The model was initially based on neuroanatomical evidence that the amygdala, which LeDoux considers to be the center of integration of affective information, receives sensory input via two routes. One pathway, the ''low road,'' carries sensory data directly from the sensory thalamus. This information is crude as its features have not been elaborated by the sensory cortex and its implications have not been analysed by the frontal cortex. The processed version of this information is fed into the amygdala by the other pathway, characterised as the ''high road''. Thus, the activity of the amygdala and the ensuing responses reflect the constantly updated balance between these two inputs. According to LeDoux, the ''low road'' appears to be involved in the processing of ''relatively simple sensory cues'' (LeDoux, 1989, p. 274) whereas the ''high road'' may be involved in processing more complex stimuli and ''cognitive information'' (p. 276) from the hippocampus and the cortex.

Although LeDoux's work has concentrated on visual and auditory stimuli, he has pointed out that the amygdala also receives extensive interoceptive inputs (LeDoux, 1989). In fact, there is extensive evidence that respiratory and cardiac activity, blood pressure fluctuations, stimulation of baroreceptors and chemoreceptors, and various modalities of noxious somatosensory stimulation are reflected in the activity of the amygdala, suggesting that its involvement during exercise is highly likely. This was supported in a study in rats, in which exercise led to increases in glucose utilisation by 56% in the central nucleus, 33% in the lateral nucleus, and 18% in the medial nucleus of the amygdala (Vissing, Andersen, & Diemer, 1996). Importantly, in addition to extensive cortico-amygdala connections from the somatosensory cortices (McDonald, 1998), interoceptive cues reach the amygdala via multiple subcortical routes (i.e., multiple ''low roads''). In addition to the thalamo-amygdala pathway, there are projections from other areas, including the nucleus of the solitary tract (Ottersen, 1981; Ricardo & Koh, 1978), the parabrachial nucleus (Bernard, Alden, & Besson, 1993), and a spinal projection (Burstein & Potrebic, 1993). Furthermore, the amygdala receives input about the internal state of the body from several subcortical areas known to be involved in cardiovascular, respiratory, and endocrine regulation during exercise, including the ventrolateral medulla (Roder & Ciriello, 1993) and hypothalamic nuclei (Ottersen, 1980).

A critical issue, and one that has stimulated criticism toward LeDoux's model, is identifying the mechanism that determines whether information about a sensory event should reach the amygdala via the ''low road'' as opposed to the ''high road''. The challenge from a theoretical standpoint is that the determination of whether the adaptive advantage is to be had by responding to a given stimulus on the basis of the quick but crude input of the ''low road'' or the slow but enriched input of the ''high road'' almost begs the invocation of a homunculus at the subcortical level. Clore and Ortony (2000) argued that, for the amygdala to be activated via the thalamo-amygdala route when seeing a snake on the ground, as LeDoux has suggested, some recognition and evaluation of the adaptational significance of the snake must take place but these functions constitute cognitive processing. It is important to recognise that, although this may be a relevant point of contention in the case of exteroceptive stimuli, whose form must be distinguished from other forms and their symbolic meaning must be appraised, the scenario may be simpler in the case of interoceptive stimuli such as those associated with exercise. This is because perhaps most of the adaptational significance of interoceptive cues may already be encoded in their intensity. Research on the physiology of interoceptors suggests that the intensity or severity of the stimulus is reflected in the pattern of firing of different classes of interoceptors (Cervero, 1994). Thus, the information that is essential for survival, namely the degree of dysregulation of the internal state, can be reflected in the pattern of activation of the interoceptive neurons. This information does not need to undergo recognition or evaluation in the sense implied by cognitive models of emotion. Instead, the determination of the significance of these cues for survival can be made on the basis of their intensity by nuclei that act as gates, allowing only the flow of impulses that exceed a critical level of intensity. In addition to the sensory thalamus, other nuclei may also serve a gating function, including the lateral nucleus of the amygdala, the entry point of most sensory input into the amygdaloid complex (Lang & Pare, 1998). Theoretically, these gates could be responsible for directing interoceptive impulses toward the cortex or directly toward the amygdala, depending on their intensity. Preliminary evidence is consistent with this possibility. In rats, stimulation using an air-puff resulted in an average delay of 61 ms until the response of the lateral nucleus of the amygdala (Uwano, Nishijo, Ono, & Tamura, 1995), whereas the corresponding value using an electric foot shock was only 17 ms (Romanski, Clugnet, Bordi, & LeDoux, 1993). This difference could indicate that the impulse from the more intense foot shock reached the amygdala via a shorter route, bypassing the cortex.

Based on the preliminary evidence from exercise studies and the information from neuroscience, it is reasonable to speculate that affective responses to exercise are the products of the continuous interplay between two general factors, both of which have access to the affective centres of the brain (i.e., the amygdala, but also other areas not discussed here, such as the anterior cingulate and insula): (a) relevant cognitive processes originating primarily in the prefrontal cortex and involving such processes as appraisals of the meaning of exercise, goals, self-perceptions including self-efficacy, attributions, and considerations of the social context of exercise and (b) interoceptive cues from a variety of receptors stimulated by exercise-induced physiological changes, which reach the affective centres of the brain via oligosynaptic subcortical pathways. Because of the assumed dual influences on affective responses, this conceptualisation is referred to as the *''dual-mode'' model*. Neither mode is likely to have complete control over affective responses to exercise. Instead, the relative salience of the two types of influences is likely to change as a function of exercise intensity. In healthy humans, the cognitive factors probably remain as the most salient influence on affective responses through the larger part of the functional range of exercise intensity. Because these cognitive processes are shaped to a large extent by experience and depend on individual developmental histories, affective responses that rely on cognitive processes are likely to vary from individual to individual. On the other hand, when exercise intensity precludes the maintenance of a physiological steady state and begins to pose a threat, the balance is likely to shift, so that interoceptive cues become the primary source of influence. Because of the limited plasticity of the subcortical pathways that carry interoceptive information to the affective centres of the brain compared to cognitive mechanisms, the inter-individual variability of affective responses that depend primarily on interoceptive influences is likely to be limited. Interoceptive influences on affective responses are also likely to be salient for a short period immediately following intense exercise. During this period, inter-individual variability in affective responses is again likely to be limited. I hypothesize, based on Solomon's (1980, 1991) opponent-process model, that, during this period, the removal of the noxious interoceptive cues associated with strenuous exercise (i.e., Solomon's *a*-process) allows the effects of the already activated endogenous opiates on respiratory and cardiovascular functions to manifest themselves (i.e., Solomon's *b*-process), beginning the return of the organism to a state of biological and affective equilibrium. In essence, the activation of the endogenous opiate system during exercise is viewed here as playing a role analogous to that which they have been known to play in stimulation- or stress-induced analgesia. In response to the stimulation or stress of exercise, the endogenous opiates may, in addition to analgesia (Droste, 1992), facilitate the process of returning physiological parameters such as respiration and blood pressure to normalcy. As in the case of stimulation- or stress-induced analgesia, this function may be controlled by the connection between the amygdala and the periaqueductal gray (Rizvi, Ennis, Behbehani, & Shipley, 1991).

The dual-mode model is primarily intended to stimulate new research into the relationship between exercise and affect. The process of designing studies to formally test the various aspects of the model is only now getting under way. The preliminary supporting evidence comes from three sources, namely (a) correlations of valence with cognitive and physiological variables across increasing levels of exercise intensity, (b) patterns of interindividual variability in affective responses, and (c) correlations of affect with indices of frontal cortical activity.

First, in two recent studies, we determined the levels of exercise intensity that were used in relation to the ventilatory threshold, as an index of the point of transition from aerobic to anaerobic metabolism (Ekkekakis et al., 1999b, 2002). These are also the only known studies that included assessments of physiological parameters and of a cognitive correlate of affective responses to exercise, namely self-efficacy. As noted in the review of the literature, in the study by Ekkekakis et al. (1999b), in which the speed and grade of the treadmill was increased every minute until the participants reached the point of volitional exhaustion, self-efficacy was significantly correlated with affective valence near the middle of the range of exercise intensity (from one minute before the ventilatory threshold to one minute before exhaustion), but not in the early stages or at the point of volitional exhaustion. On the other hand, the correlation between the respiratory exchange ratio and affective valence reached statistical significance from the first minute after the ventilatory threshold and until the point of exhaustion. Entering both self-efficacy and the respiratory exchange ratio data into a hierarchical regression (with self-efficacy first), showed that, below the ventilatory threshold, self-efficacy was responsible for almost all (approximately 80–100%) of the total accounted variance in affective valence (total R^2 between 12% and 23%). On the other hand, at intensities above the ventilatory threshold, the respiratory exchange ratio began to account for increasingly larger amounts of variance. From the second minute after the ventilatory threshold and until exhaustion, the respiratory exchange ratio was responsible for most (approximately 65–80%) of the total accounted variance in affective valence (total R^2 between 34% and 55%). In another study (Ekkekakis et al., 2002), which involved running at a constant speed at three levels of intensity, below, at, and above the ventilatory threshold, self-efficacy and the highest percentage of maximal heart rate attained during exercise jointly accounted for approximately 30% of the variance in changes in affective valence over the course of each of the three runs (note that the percentage of maximal heart rate is generally a weaker correlate of affective valence compared to the respiratory exchange ratio, but respiratory data were not collected in this study). Although self-efficacy accounted for approximately two thirds and nearly all of this variance at the intensities below and at the ventilatory threshold, respectively, it only accounted for less than half at the intensity above the ventilatory threshold. Although these are interesting results, they are limited in several respects, including the correlational nature of the studies and the relatively small sample sizes (N = 30 in both studies). Furthermore, the range of exercise intensities in these studies did not include intensities as low as those found in our studies on walking (Ekkekakis et al., 2000). As noted earlier, the mechanisms behind the positive changes associated with walking remain unexplored. Given the very low level of physiological activation involved, it is possible that these responses may be influenced by some yet unknown cognitive factors. At the same time, the possibility that these positive affective responses are the manifestations of a biological mechanism that has evolved to reward and, thus, promote physical activity and, through that, the maintenance of a healthy balance between energy intake and expenditure (Rowland, 1998) should not be discounted. For instance, it is intriguing that lesions of the amygdala in young rats lead to decreases in spontaneous play activity (Panksepp, Siviy, & Normansell, 1984).

Second, some insight about the substrates of affective responses to exercise of different intensities and during different stages of an exercise bout may come from examining changes in patterns of inter-individual variability in valence ratings. As noted earlier, high inter-individual variability may be interpreted as an indication that the responses are influenced primarily by cognitive processes, whereas low inter-individual variability may be an indication that the responses are driven primarily by the evolutionarily more ancient and less plastic connections between interoceptive pathways and the affective centres of the brain. Responses that depend on these lower brain processes are generally characterised as rigid, stereotypical, or obligatory (Berntson & Cacioppo, 2000). This line of reasoning, of course, is not without some risk, as it is possible that, under certain conditions, most individuals simply make the same cognitive appraisal via higher brain processes. Nevertheless, these analyses may still be informative in conjunction with other types of evidence. Examination of the patterns of inter-individual variability in changes in affective valence shows that variation is higher when exercise intensity is low to moderate and during recovery from exercise (Ekkekakis et al., 2000, Hall et al., 2002). Particularly during moderate-intensity exercise, valence responses can vary greatly from individual to individual, not only in terms of magnitude but also in terms of direction, with some individuals exhibiting improvements and others declines (Van Landuyt et al., 2000). On the contrary, inter-individual variation in valence responses are minimised as exercise intensity approaches the physical limits of individuals (in which case, valence changes are almost universally negative) and during the first minute after the termination of strenuous exercise (in which case, valence changes are universally positive; Hall et al., 2002). If these differences in the patterns of inter-individual variability indicate shifts between the two postulated sources of influence on valence responses, these results would seem consistent with the dual-mode model.

A third and final line of evidence that affective responses to exercise of different intensities may engage different mechanisms comes from a series of studies examining the relationships between the asymmetric activation of the brain's prefrontal lobes (assessed through electroencephalography, or EEG) and affective responses. According to Davidson's (1995) model, frontal asymmetry is a biological marker of approach versus avoidance dispositions. These dispositions manifest themselves as propensities for positive and negative affective responses, respectively. Specifically, more right-activated individuals may tend to respond to affective stimuli in a more negative or less positive manner, whereas, conversely, more left-activated individuals may respond in a more positive or less negative manner. Davidson and Fox (1988) have noted that ‘‘precisely what the frontal asymmetry represents will require additional research’’, but ‘‘appraisal and coping are two subcomponents that may be related to the frontal asymmetries’’ (p. 204). If that is so, frontal asymmetry can be interpreted as reflecting primarily cognitive processes involved in affective responses. The studies that have been conducted in the context of exercise have shown that baseline frontal asymmetry is related to affective responses (in these cases, changes in the Energetic Arousal scale of the AD ACL; Thayer, 1989) when exercise intensity is moderate (70–75% of maximal aerobic capacity), but not when it is low or high (Hall, Ekkekakis, Van Landuyt, & Petruzzello, 2000; Petruzzello, Hall, & Ekkekakis, 2001; Petruzzello & Landers, 1994; Petruzzello & Tate, 1997). Again, the interpretation of these results as supporting the dual-mode model rests on the assumption that frontal asymmetry reflects primarily cognitive processes, such as appraisal and coping.

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