Imagination of dynamic exercise produced ventilatory responses which were more apparent in competitive sportsmen

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1. The cardiorespiratory response to imagination of previously performed treadmill exercise was measured in six competitive sportsmen and six non-athletic males. This was compared with the response to a control task (imagining letters) and a task not involving imagination ('treadmill sound only').
2. In athletes, imagined exercise produced increases in ventilation which varied within and between subjects. The mean maximal increase (11·7 l min^{-1}) was approximately 20% of the ventilatory response to actual exercise. This was primarily due to treadmill speed-related increases in respiratory frequency (mean maximal increase, 14·8 breaths min^{-1}) and resulted in significant reductions in end-tidal P_{CO_2} (mean maximal fall, 7 mmHg). These effects were greater ($P < 0·01$) than any observed during the control tasks.
3. Changes in heart rate (mean increase, 12 beats min^{-1}) were not significantly different from those observed during the control tasks ($P > 0·2$).
4. In non-athletes, imagination of exercise produced no changes in cardiorespiratory variables. No significant differences were detected in subjective assessments of movement imagery ability between athletes and non-athletes ($P = 0·17$).
5. This study demonstrates that ventilatory effects, when observed, are specific to imagination of exercise. The greater likelihood of generating ventilatory responses in highly trained athletes, experienced in 'rhythmic' sports, may be related to awareness of breathing and its role in exercise imagination strategy. A volitional component of the response cannot be discounted.

Breathing in man relies on both an automatic system of control subserved by respiratory-related neurones located in the brainstem, and a behavioural system of control originating from suprapontine areas. Behavioural control of breathing can be as overt as a deliberate (volitional) decision to take a deep breath, an act which has been demonstrated to be associated with neuronal activation of the motor cortex in man (Colebatch *et al.* 1991; Ramsay *et al.* 1993). However, behavioural effects on breathing are also apparent in the more subtle changes accompanying vocalization or changes in emotional state. The neural basis of the behavioural system of control therefore, includes corticospinal and/or corticobulbar pathways which permit voluntary modification of breathing, but also probably involve additional pathways from other suprapontine areas such as the limbic system. Recent clinical evidence indicates that emotions can affect breathing when volitional respiratory control is lost, following a lesion of the corticospinal tract (Munschauer, Mador, Ahuja & Jacob, 1991).

During exercise, it has been generally assumed that the increase in ventilation results from stimulation of the automatic system of control via afferent feedback from chemical and mechanical receptors. However, a purely automatic mechanism may not be adequate to explain fully changes in ventilation during exercise. Exercise hyperpnoea could depend, at least in part, upon neural activity from the motor cortex, as originally suggested by Krogh & Lindhard (1913). Recent studies in children with congenital hypoventilation syndrome (Shea, Andres, Shannon & Banzett, 1993) and adults with medullary lesions (Heywood, Moosavi, Morrell & Guz, 1993) showed that these groups have an appropriate ventilatory response to exercise despite clear evidence of dysfunctional automatic respiratory control.

In normal man, it has been demonstrated that ventilation can be stimulated during anticipation of exercise (Tobin, Perez, Guenther, D'Alonzo & Dantzker, 1986); presumably, this reflects activation of higher brain mechanisms in

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preparation for the exercise. In addition, studies using hypnosis as a physiological tool have shown that ventilation can be stimulated by the 'suggestion' of exercise in the absence of peripheral feedback related to movement or chemical stimulation (Dudley, Holmes, Martin & Ripley, 1964; Daley & Overley, 1966) and by the 'suggestion' of 'higher' work intensities (Morgan, Raven, Drinkwater & Horvath, 1973). It is interesting to speculate that changes in breathing during hypnotic suggestion of exercise reflects a behavioural component of exercise hyperpnoea; however, the lack of a clearly defined neurophysiological basis to hypnosis makes it difficult to interpret such studies.

More recently, mental imagery of exercise in the awake state has been shown to produce increases in both ventilation and heart rate which are proportional to the intensity of imagined exercise (Decety, Jeannerod, Germain & Pastene, 1991). However, a detailed physiological description of the respiratory responses associated with imagination of dynamic exercise is lacking. The aim of the present study was to test whether the reported cardiorespiratory effects are specific to imagination of exercise, as opposed to imagination in general, and to assess the reproducibility of these effects within and between individuals. An attempt was also made to address the subjective experience of imagined exercise using structured interviews.

METHODS

Subjects

Twelve male subjects, aged between 22 and 41 years and with no history of cardiorespiratory disease, were studied in the exercise laboratory. Six of these (group 1) were highly trained competitive athletes whose principal sporting events were: middle-distance running (2 subjects), 400 m hurdles, squash, rowing and 'ultra-fitness' cross training. The other six subjects (group 2), two of whom smoked 1–2 cigarettes per day, were chosen as active and generally fit individuals who were not competitive sportsmen and not involved in any form of training. Ten of the twelve subjects had never experienced exercise testing in a laboratory setting, although the three runners in group 1 had experienced training on a treadmill. All subjects gave informed written consent to participate in the study.

Subjective assessment of imagery ability

Before recruitment, each subjects' ability to perform mental imagery was assessed by responses to standard questionnaires. Firstly, a shortened form of Bett's questionnaire upon mental imagery (Sheehan, 1967) was used by the subjects to rate the vividness of a variety of visual, auditory, tactile, kinaesthetic, gustatory, olfactory and sensory images. The questionnaire was given to each subject to complete when alone and in their own time. Secondly, a modified version of a movement imagery questionnaire (Hall & Pongrac, 1983) was given to the subjects to complete in a quiet room just prior to the first experimental session. This involved a number of movement sequences which were actually performed and immediately followed by mental imagery of the same sequences. These mental images were subjectively rated, on a scale of one to seven, in terms of the 'vividness' of the image, ranging from *very easy* to *very hard to picture*. The subjects also rated, on the same scale, the ease with which they could 'feel themselves' making the movement, ranging from *very easy* to *very hard to feel*. These questionnaires provided a means of assessing the ability of subjects to imagine as well as an opportunity for mental practice of imagery tasks.

Measurements and procedures

Following a preliminary visit during which subjects were introduced to the laboratory environment and equipment, each subject attended the laboratory on two further occasions (session 1 and 2) separated by between 1 and 8 days. They were aware that these sessions would involve short periods of exercise on a treadmill, as well as certain mental imagery tasks, during which heart rate and other physiological and subjective changes would be recorded. The subjects were informed that one of the mental imagery tasks would be to 'imagine' exercise by feeling themselves exercising, as opposed to just visualizing the exercise 'from the outside' (i.e. from a first-person rather than a third-person perspective). However, they were kept unaware of the precise aims of the study and care was taken to disguise the experimenters' specific interest in breathing.

Cardiorespiratory measurements

Subjects breathed through a medium-sized adult face mask (Hans Rudolph Inc., Kansas City, MO, USA) adapted for breathing through the mouth and the nose. This was connected to a heated Fleisch pneumotachograph (size 2; P. K. Morgan, Rainham, Kent, UK) which gave continuous measurements of airflow; the total extra dead space amounted to 120 ml. Repiratory frequency (f_R), tidal volume (V_T) and minute ventilation ($\dot{V}_E$) were derived from the airflow signal and samples of mixed expired air yielded estimates of O_2 uptake ($\dot{V}_{O_2}$) and CO_2 production ($\dot{V}_{CO_2}$). All values were computed using an automated exercise analysis system (Ergostar; Fenyves and Gut, Basel, Switzerland). End-tidal P_{CO_2} (P_{ET,CO_2}) was measured using a rapidly responding infrared analyser (LB2; Beckman Instruments Inc., Fullerton, CA, USA); this measurement was corrected to provide a better estimate of arterial P_{CO_2} on exercise (Jones, Robertson & Kane, 1979). Heart rate (f_C) was derived from a three-lead electrocardiogram (C.A.S.E.; Marquette Electronics Inc., Milwaukee, WI, USA). All variables were recorded as 30 s averages. Analogue signals were recorded on an FM tape recorder (Store 4; Racal, Hythe, Hampshire, UK) and simultaneously on a chart recorder (ES1000; Gould, Ballanvilliers, France).

Protocol

During each of the two sessions, the subjects performed four 9 min tasks, one of which involved actual treadmill exercise (task A). The other three tasks, which were performed standing on a purpose-built platform above the moving treadmill, involved the imagination of the same exercise (task B), a control mental imagery task which required subjects to visualize the letters of a nursery rhyme (task C) and a non-specific control state for which no prior instructions were given for any particular imagery (task D). All task-specific instructions were delivered to the subjects via headphones in standardized (pre-recorded) form. A surface electromyographic electrode applied to the subject's left quadriceps was used to detect footsteps during the exercise task.

Session 1

For the 3 min immediately prior to each task, subjects stood astride the treadmill which was screened off from the rest of the laboratory. During the first 2 min, baseline cardiorespiratory measurements were obtained. Over the third minute subjects received a task-specific instruction. For example, in the case of imagined exercise (task B) subjects received the following message:

> 'You will hear the treadmill start and soon after that a tone. When you hear the tone, step onto the platform being placed in front of you. Stand quietly with your eyes closed and your arms at your sides. For the rest of the run, imagine you are exercising on the treadmill, just as you did for the last run. Maintain a clear and vivid image of how you felt yourself moving at the different treadmill speeds.'

Prior to these instructions, subjects were unaware of the task to be undertaken; this ensured that the baseline measurements were not affected by anticipation of any particular task. If the task to be performed did not involve actual exercise, a platform was placed astride the treadmill belt for the subject to stand on during the task. At the end of this initial 3 min period, a tone, played via the headphones, signalled the subject to start the required task.

For task A, subjects stepped onto the moving treadmill belt and began exercising. They performed three consecutive 3 min periods of exercise at the following speeds: 4·8, 8 and 12 km h^{-1} (speeds 1, 2 and 3, respectively). The speeds represented typical walking, jogging and running paces. A brief message was given over the headphones at the start of each level of exercise announcing speed 1, 2 or 3.

For non-exercise tasks (B, C and D), the subjects stepped onto the platform in front of them, instead of the moving treadmill belt. They then stood with eyes closed and arms at their sides throughout the remainder of the task. During these tasks, the treadmill speeds (speeds 1, 2 and 3) were the same as that during task A; this ensured that the subjects were exposed to similar treadmill vibrations and sounds as during actual treadmill exercise. For task B (imagined exercise), subjects received brief announcements about the treadmill speed as they had during actual exercise. Task C (visualizing letters) was also divided into three phases to make it equivalent to the actual and imagined-exercise tasks; subjects were instructed to visualize letters with right angles (e.g. E), curved lines (e.g. S) or sloping lines (e.g. A) during treadmill speeds 1, 2 and 3, respectively. Thus, at the start of treadmill speed 1 subjects received the following message:

> 'For the next few minutes find those letters which have lines making perfect right angles. Find them, count them, memorize them.'

During task D (treadmill sounds only), no equivalent messages were given at the start of each treadmill speed. During all tasks, subjects also heard a synchronized prerecording of treadmill sounds reflecting the changes in treadmill speed. At the end of each task, the treadmill was gradually stopped while the subjects received a final message instructing them to stop performing the task and to return to the resting state during which a further minute of recovery data was obtained.

In session 1, all subjects first performed task D (treadmill sounds only) followed by A (actual exercise), B (imagined exercise) and finally C (visualizing letters). This order of tasks ensured that the treadmill-sound only control task (D) was not influenced by any previous task and that all subjects had an opportunity of actually performing the exercise (task A) before attempting to imagine it (task B). At least 5 min of rest were provided between tasks during which subjects relaxed seated in a chair. Following actual exercise (task A), subjects were given at least 15 min to recover.

Session 2

In this session, imagined exercise (task B) was performed first to see whether any response in session 1 would be carried forward on a later day without potential reinforcement by immediately prior exercise. This was followed by task C (visualizing letters), task D (control task) and finally task A (actual exercise). Apart from this difference in task order, session 2 was otherwise identical to session 1.

Subject debriefings

Structured interviews were conducted at various times in an attempt to assess the subjects' experiences. Firstly, during the rest intervals, subjects were invited to comment on their experience during the task just completed. Volunteered comments were followed by the specific enquiry:

> 'What were you mostly attending to or thinking about during that run?'

In addition to this, after tasks B (the imagined exercise) and C (visualizing letters), the subjects were asked to scale the vividness of the mental images and feelings on a five-point scale ranging from 'no image' to 'extremely vivid image'. They were also asked to comment on whether they could maintain the vividness of the image throughout the run. In the case of task B, subjects indicated the parts of their body of which they had the clearest mental image. After completion of both sessions, a final debriefing was carried out. Initially, the subjects were asked to comment on what they thought the experiments were concerned with. Only at this stage were they asked specifically whether they were aware of breathing sensations or changes in breathing during task B and whether they had 'used their breathing to help them to better imagine exercise'. Group 1 subjects were asked whether they 'entrained' their breathing with their strides during exercise, and whether they were making such changes in breathing during imagined exercise.

Data analysis

Over the 9 min period of each task, each successive 30 s measurement of $\dot{V}_E$, f_R, V_T, f_C, $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$ and P_{ET,CO_2} (corrected) was averaged across subjects for groups 1 and 2 separately ($n = 6$ for each group).

Analysis of baseline resting levels prior to each task

The 2 min baseline levels (mean of 4 successive 30 s measurements) prior to each of the four tasks were analysed using a three-factor (1 between, 2 within) analysis of variance

(ANOVA; BMDP 2V; Dixon, 1990). The *between* factor was the group (athletes and non-athletes) and the two *within* factors were: session (1 and 2) and condition (1, 2, 3 or 4). In this case, condition represented the order number of the task and not the nature of the task.

Comparison of the response to actual exercise between groups

Changes in the absolute values of each variable over the 9 min of actual exercise were compared between groups using a three-factor (1 between, 2 within) ANOVA. The between factor was the group (athletes and non-athletes) and the two within factors were: session (1 and 2) and time (30 s periods).

Individual ventilatory responses to imagined exercise

For each of the two sessions in each of the twelve subjects the ventilatory response to imagined exercise (task B) was compared with the ventilatory response to actual exercise (task A). An individual ventilatory response to imagined exercise was classed as a 'good response' if all of the following criteria were satisfied: (i) a slope of linear regression significantly greater than zero ($P < 0{\cdot}05$), (ii) level of $\dot{V}_E$ during imagined exercise rose above +2 S.D. of the mean pretask baseline level of $\dot{V}_E$, and (iii) a slope of linear regression greater than 0·2 (i.e. ventilatory response to task B is greater than 20% of the ventilatory response to task A). A 'weak response' to imagined exercise was assigned if criteria (i) and (ii) were satisfied but the ventilatory response to task B was between 10 and 20% of that during task A (i.e. slope of linear regression between 0·1 and 0·2). A 'non-response' was assigned if any of the above criteria were not satisfied.

Group mean response to imagined exercise compared with (non-exercising) control tasks

For each variable, tasks B (imagined exercise), C (visualizing letters) and D (treadmill sound only) were compared using a three-factor analysis (all within) of covariance with repeated measures (ANCOVA; BMDP 2V; Dixon, 1990). The three within factors were: session (1 and 2), condition (B, C or D), and time (30 s periods). The covariate for each variable was the mean level during the respective 2 min baseline periods prior to tasks B, C and D. This analysis was performed for groups 1 (athletes; $n = 6$) and 2 (non-athletes; $n = 6$) separately. From the ANCOVA, a Fisher's least significance difference (LSD)

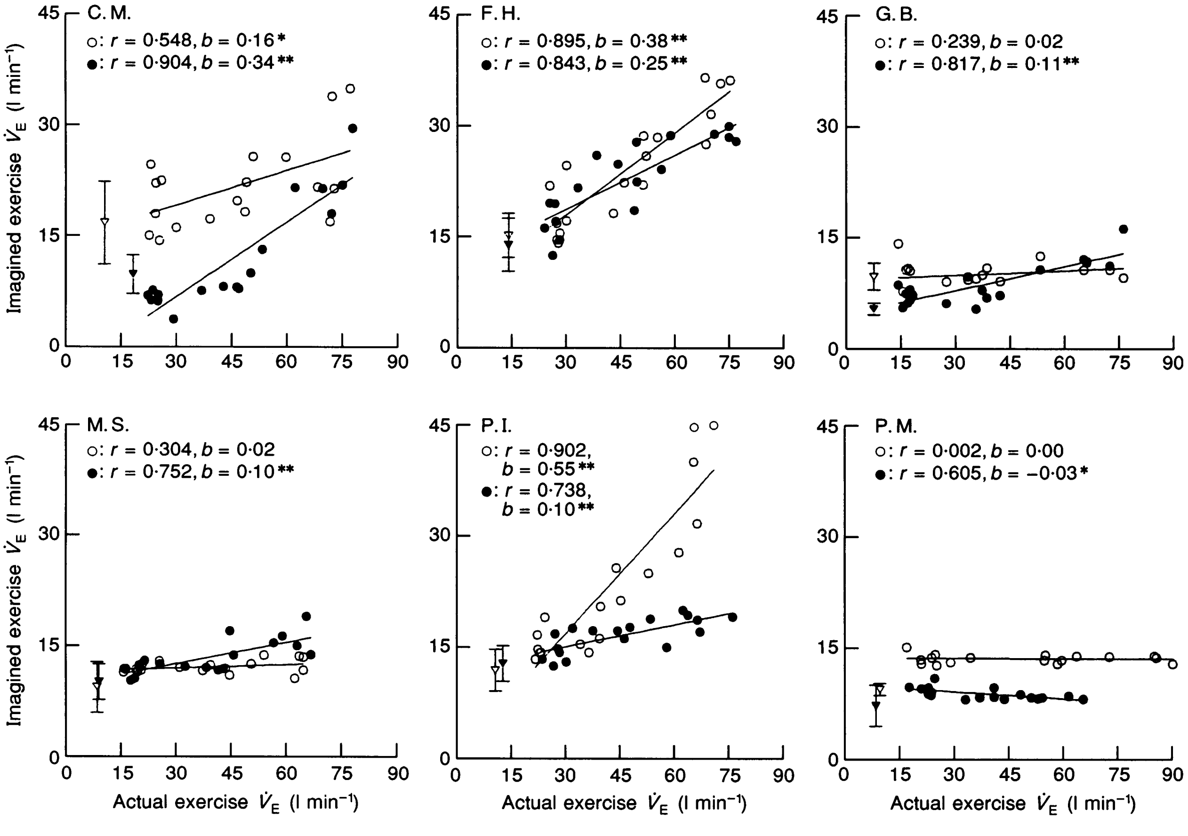

Figure 1. Comparison of $\dot{V}_E$ responses to imagined and actual exercise in athletes

Each successive 30 s measurement of ventilation ($\dot{V}_E$) during the 9 min of imagined exercise is plotted in relation to the equivalent 30 s measurement of $\dot{V}_E$ during actual exercise for sessions 1 (○) and 2 (●) in individual subjects of group 1 (athletes). The resting $\dot{V}_E$ (mean of 4 consecutive 30 s measurements) during the baseline period prior to the tasks is shown for sessions 1 (▽) and 2 (▼). Vertical error bars represent ± 2 S.D. of the mean baseline $\dot{V}_E$ prior to the imagined-exercise task. Continuous lines indicate linear regression by least squares for each session. The correlation coefficient (r) and the slope (b) of the linear regression are indicated for each individual. Significantly greater than zero value for b is given as * $P < 0{\cdot}02$ or ** $P < 0{\cdot}001$.

statistic ($P < 0{\cdot}05$) was calculated to allow comparison of mean levels measured over successive 30 s intervals between tasks (Fisher, 1935). ANCOVA was chosen to take into account the variability in the pretask baseline levels of ventilation.

RESULTS

Baseline levels of cardiorespiratory variables

The mean levels of $\dot{V}_E$ (10·9 and 11·4 l min^{-1} for groups 1 and 2, respectively) and of P_{ET,CO_2} (35·5 and 31·9 mmHg for groups 1 and 2, respectively) averaged across the eight baseline periods (4 tasks on 2 occasions) indicates that, in general, subjects hyperventilated while waiting on the treadmill prior to performing a task. Baseline levels of P_{ET,CO_2} were lower, on each occasion, in the non-athletes, although this group difference did not quite reach statistical significance (ANOVA, $P = 0{\cdot}056$). For $\dot{V}_E$, no significant changes were detected in successive baseline periods prior to each task. The athletes (group 1) had a consistently lower mean f_C over the eight baseline periods (mean level 77·6 beats min^{-1}) compared with the non-athletes (mean level 88·4 beats min^{-1}) but this difference was also not significant (ANOVA, $P = 0{\cdot}172$). Despite the 15 min recovery period following performance of actual exercise, heart rates were, on average, 10 beats min^{-1} higher during the baseline period prior to the task which followed actual exercise in session 1 (ANOVA, $P = 0{\cdot}002$). This effect was not observed during session 2 since on this occasion actual exercise was the last task performed.

Response to actual exercise

Analysis of variance (ANOVA) showed that there were no significant group differences in the overall mean levels of f_C, $\dot{V}_E$, f_R, V_T, P_{ET,CO_2}, $\dot{V}_{CO_2}$ and $\dot{V}_{O_2}$ during actual exercise. The change in $\dot{V}_E$ with time appeared to be greater (ANOVA, $P < 0{\cdot}01$) for the non-athletes particularly during speed 3. This could be explained by a lower lactate 'threshold' in this group. A slight fall in P_{ET,CO_2} (to 37·5 mmHg) seen during speed 3 in the non-athletic group only is consistent with this explanation.

Apart from the squash player, all group 1 (athletic) subjects indicated that they were concentrating on their running technique throughout the exercise. In group 2, only two subjects reported that they were concentrating on their running movements. The remaining subjects indicated that they were not as focused on the exercise being performed. Three reported thinking about running in another environment and two reported thinking mainly about something unrelated to exercise. All subjects in groups 1 and 2 were concerned about their balance on the treadmill which required some degree of mental effort. In response to

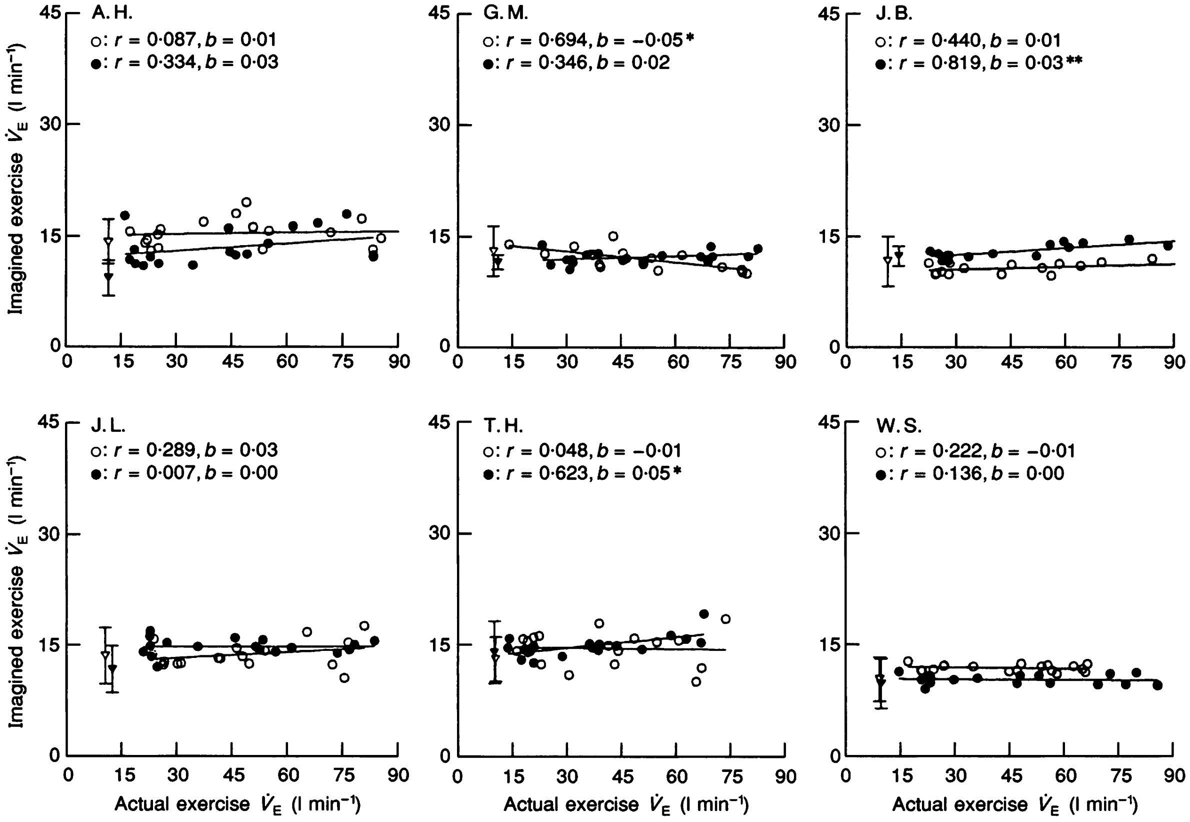

Figure 2. Comparison of $\dot{V}_E$ responses to imagined and actual exercise in non-athletes

Details as for Fig. 1.

a specific question at the end of the experiments, eight subjects (5 athletes and 3 non-athletes) revealed that they had 'timed' their breathing with their stepping frequency during actual exercise, at least for the fastest speed.

Individual responses to imagined exercise

There was considerable variability in the degree of ventilatory responses to imagined exercise between subjects. On the basis of the criteria set out above (see 'Data analysis' in Methods), four of twelve imagined-exercise runs in the six athletes (Fig. 1) can be classed as 'good responses' (F.H. both sessions, C.M. session 2, and P.I. session 1), four as 'weak responses' (C.M. session 1, G.B., M.S. and P.I. session 2) and four as 'non-responses' (G.B. and M.S. session 1, P.M. both sessions). By contrast, in the non-athletic group, only three of the twelve imagined-exercise runs showed a significantly greater than zero slope in relation to the ventilatory response to actual exercise (Fig. 2). In these three cases, either the slope of the relationship is less than 0·05 or the scatter of 30 s

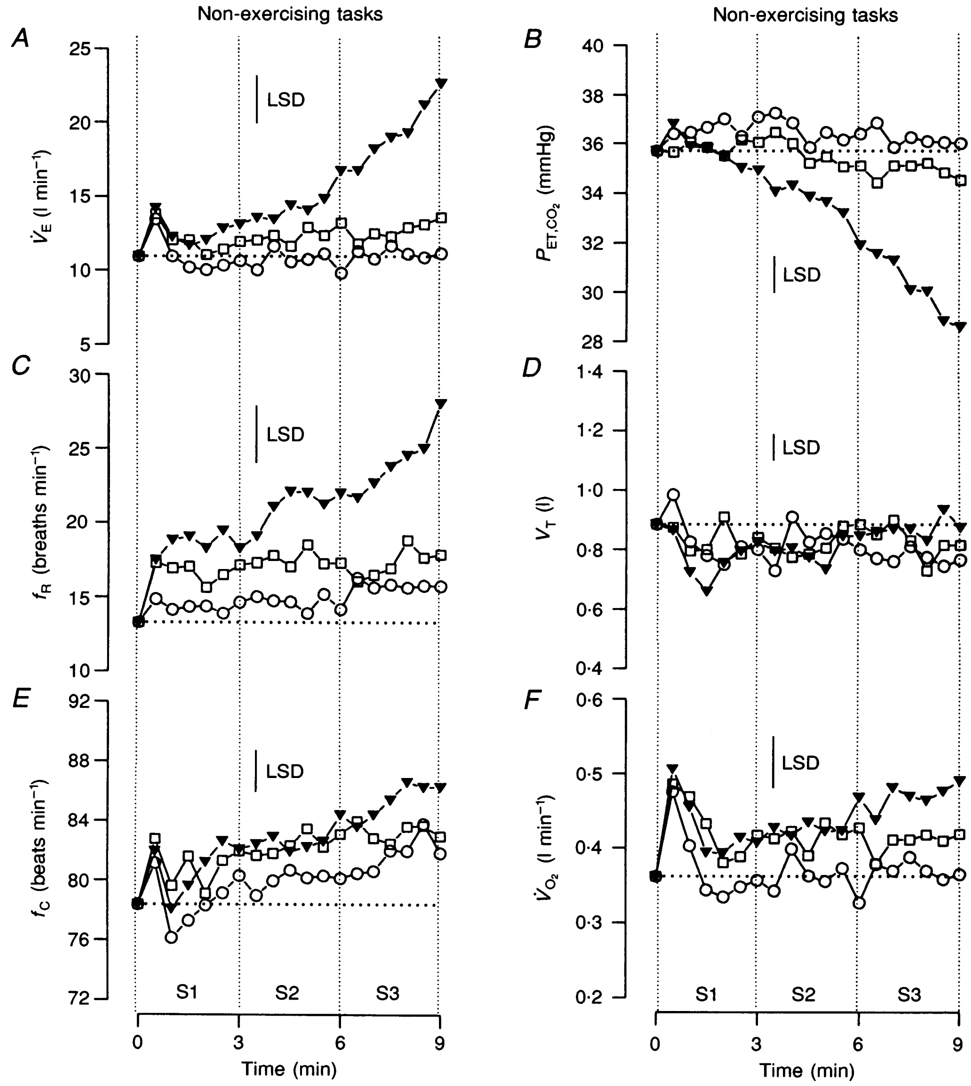

Figure 3. Mean cardiorespiratory changes during non-exercise tasks in the athletes

Mean changes in ventilation ($\dot{V}_E$), end-tidal P_{CO_2} (P_{ET,CO_2}), respiratory frequency (f_R) and tidal volume (V_T), heart rate (f_C) and oxygen uptake ($\dot{V}_{O_2}$) during imagined exercise (▼), visualizing letters (□) and the task with sounds of the treadmill only (○) for group 1 (athletes). Each point represents the mean of all breaths over successive 30 s periods averaged across subjects ($n = 6$) and sessions ($n = 2$). For each variable, the horizontal dotted line is the mean pretask baseline level for all non-exercise tasks over two sessions; each 30 s value has been adjusted for individual baseline levels. During each task, the treadmill was running at 4·8 (S1), 8 (S2) and 12 km h^{-1} (S3). Fisher's least significant difference (LSD) bars allow comparison of mean levels during the 3 tasks ($P < 0{\cdot}05$) at any time.

measurements remains within the ± 2 S.D. range of the mean resting $\dot{V}_E$ prior to the imagined-exercise task; these three runs are also therefore 'non-responses'.

Group mean responses to imagined exercise

Group 1 (athletes)

On average, group 1 subjects produced a treadmill speed-related increase in $\dot{V}_E$ accompanied by a fall in P_{ET,CO_2} during imagined exercise (Fig. 3*A* and *B*). These mean changes are predominantly due to 'good responses' in three subjects, one of whom produced a 'good response' on two occasions. The pattern of these changes over time was significantly different from those seen during the treadmill sounds-only task ($P < 0.001$ for each variable) or during the imagined-letters task ($P < 0.001$ for each variable). The mean level of $\dot{V}_E$ at any particular time is higher during the imagined-exercise task; the Fisher's LSD statistic derived from the ANCOVA indicates that it is mainly during treadmill speed 3 that the changes observed during the imagined exercise are significantly different from both of the control tasks. The increase in ventilation with time associated with the imagined-exercise task resulted from a treadmill speed-related increase in f_R (Fig. 3*C*) which was greater than that seen during both the imagined-letters task ($P < 0.001$) and the treadmill sounds-only task ($P < 0.001$). The treadmill speed-related increase in f_C during imagined exercise (Fig. 3*E*) was not significantly different from the changes with time seen for the control tasks ($P = 0.22$). The mean level of $\dot{V}_{O_2}$ (Fig. 3*F*) was significantly higher than during treadmill sound-only task ($P = 0.04$) but not different from the levels seen during the imagined-letters task ($P = 0.89$). Inspection of

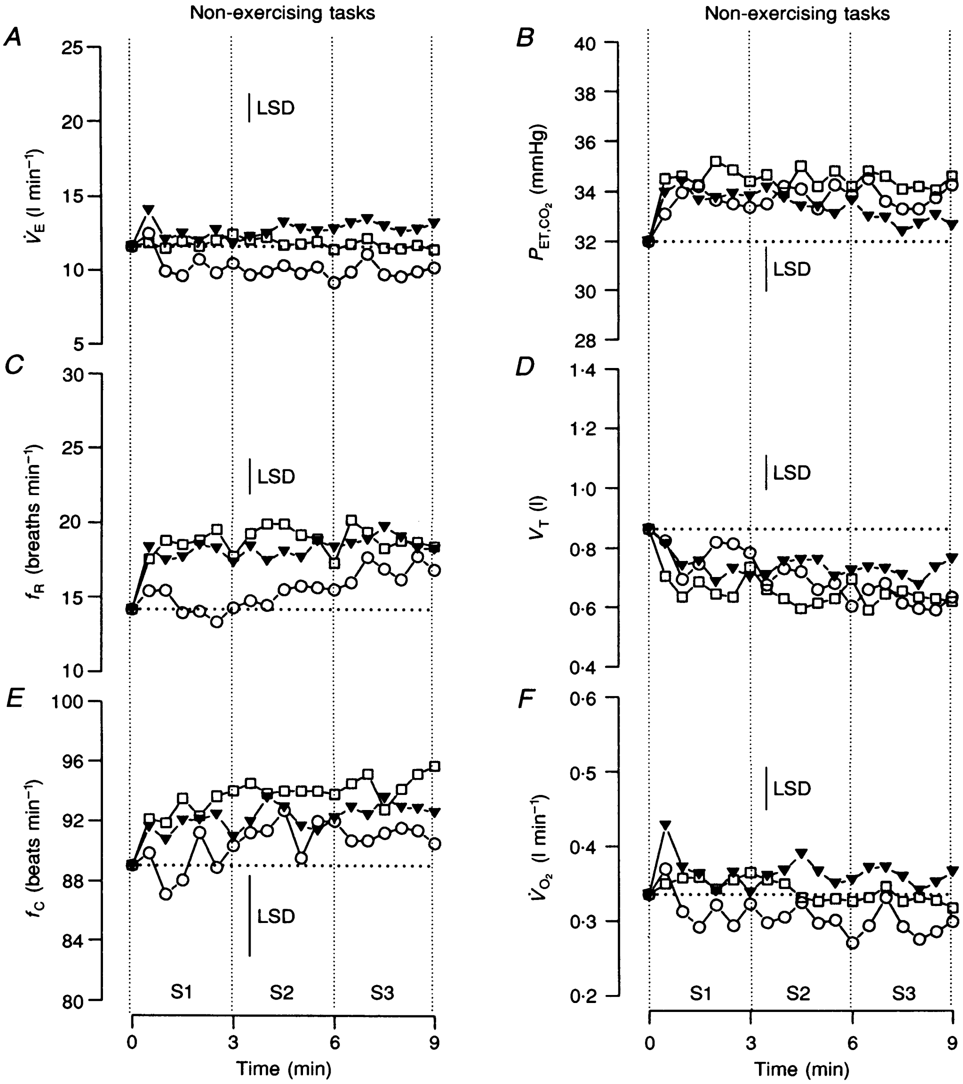

Figure 4. Mean cardiorespiratory changes during non-exercise tasks in the non-athletes
Details as for Fig. 3.

Fig. 3 reveals transient increases in $\dot{V}_E$, f_C and $\dot{V}_{O_2}$ at the onset of each task; these changes probably reflect the effect of stepping onto the platform above the treadmill immediately prior to the beginning of the tasks.

Group 2 (non-athletes)

The group data for the non-athletes do not show a clear increase in $\dot{V}_E$ associated with imagined exercise (Fig. 4*A*). ANCOVA showed that the change in $\dot{V}_E$ with time for the imagined-exercise task was significantly different from that during the treadmill sound-only task ($P = 0{\cdot}05$) but, unlike group 1, not significantly different from the imagined-letters task ($P = 0{\cdot}32$). Similarly, the mean level of f_R (Fig. 4*C*) was significantly higher during imagined exercise compared with the treadmill sound-only task ($P = 0{\cdot}02$) but not significantly different compared with the visualizing-letters task ($P = 0{\cdot}370$). No significant differences were detected in the mean level of P_{ET,CO_2} ($P = 0{\cdot}31$), or the changes in this variable with time ($P = 0{\cdot}52$), between the three non-exercising tasks for this group. In addition, there appears to be a transient non-specific rise in P_{ET,CO_2} for this group at the start of the tasks (Fig. 4*B*) which is not present in group 1; this suggests that the alveolar hyperventilation while waiting to begin the tasks in the non-athletes is partially reduced by a non-specific change in mental activity.

Subjective assessment of imagery ability

The modified Hall & Pongrac (1983) questionnaires revealed that individual subjects assessed their overall 'ability to imagine movement' (obtained from scores of 'visualizing the image' and 'feeling the movement') as ranging between points 1 (very easy) and 4 (neutral; neither easy nor hard) on a seven-point scale. The average score for athletes was 2·1 and for non-athletes was 2·9; these scores were not significantly different between the two groups ($P = 0{\cdot}17$, Wilcoxon rank sum test).

Subjects' reports on their experience during imagined exercise

Comments on vividness and nature of imagery

The reports of the subjects indicate that they were all able to form a mental image of themselves exercising for at least part of the 9 min imagined exercise task. On average, subjects rated the peak vividness of images as 'strong' (point 2 of a 5-point scale ranging from 'extremely vivid' image (1) to 'no image' (5)). The images were not always equally vivid throughout the task; one athlete and two non-athletes indicated that vivid images occurred only transiently following speed changes, whilst three subjects in each group indicated that the most vivid images occurred during a specified period. This was usually the running speed for athletes and mainly the walking or jogging speed for the non-athletes. Reasons given for the fluctuations in vividness were either distractions due to the equipment or changes in concentration. Imagination strategy involved clear mental images of bodily movements associated with actual exercise. These included various combinations of swinging arms, trunk, hips, as well as leg, head, or upper body movements. In addition, two athletes and one non-athlete indicated that they also used mental representations of external environments such as a familiar running field or being involved in a race or a competition to help imagination.

Comments on breathing awareness

Post-test volunteered comments by the subjects tended to indicate that breathing awareness during imagined exercise was based either on a perception of an unexpected modification of the breathing pattern, e.g. F. H.:

> '... I suddenly realized my breathing was heavy and, I mean, I did nothing but stand there, so ... it shouldn't be but I could really feel ... as if I was doing something and when [the experimenter] announced 'speed 3' ... again my breathing was up ...'

Or on a tendency to use breathing as part of the imagination strategy, e.g. A. H.:

> 'I imagined ... being out of breath and breathing harder. I think actually my breathing changed a bit as well as I was imagining it.'

Or P. I.:

> 'I found that breathing was a funny thing throughout the run. I got myself into my normal breathing exercise pattern ...'

Not all subjects volunteered comments on breathing awareness but, when directly questioned during the final debriefing, the majority of subjects in both groups revealed that they were aware of breathing or changes in breathing during imagined exercise. Only one subject in each group, both of whom were 'non-responders', did not report any perception of breathing. Four of six subjects in group 1 reported attempts to time their breathing with their (imagined) strides. Finally, when specifically asked: 'Did you use your breathing to help you to imagine exercise?', four subjects in group 1 and two subjects in group 2 reported that this was so.

DISCUSSION

This study demonstrates that in a group of highly trained competitive sportsmen, imagination of treadmill exercise produces a treadmill speed-related increase in ventilation which amounts to approximately one-fifth of that observed during actual performance of the same exercise. This approximation reflects large increases in some athletes (up to 50% of that observed during actual exercise) and minimal or no increases in other athletes. When such an effect is apparent, it is primarily due to treadmill speed-related increases in respiratory frequency and is associated with significant reductions in end-tidal P_{CO_2}. The same protocol in a group of healthy, but non-athletic, subjects did not generate increases in ventilation which were different from those observed during a control imagination state (visualizing letters). Comments from the subjects following imagined exercise suggest that the most pronounced ventilatory responses were associated with awareness of breathing and its possible use as part of the strategy to imagine exercise.

The mean increase in ventilation of 11 l min^{-1} in the group of athletes closely resembles that recently reported by Decety *et al.* (1991) in a group of ten physical education students during imagination of an exercise protocol identical to the one used in the present study. Other studies using the hypnotic suggestion of exercise have reported even greater ventilatory responses than those seen with imagination of exercise in the 'awake' state (Daley & Overley, 1966). Presumably in the hypnotized state, 'hallucination' of exercise is uncorrupted by other mental processes associated with 'wakefulness'. In studies involving hypnotic suggestions of exercise, subjects are usually recruited on the basis of an underlying susceptibility to hypnosis. In the present study, the movement imagery questionnaire revealed that subjects rated their ability to imagine a previously performed movement as 'easy'. No difference was detected between athletes and non-athletes in this subjective assessment, nor was there any indication that those subjects with higher ventilatory responses had better imagery ability. This does not, however, exclude the possibility that subtle differences in the ability to imagine could have contributed to individual variability and reproducibility of the ventilatory responses.

More recently, cardiorespiratory responses to the imagination of other forms of exercise have been reported. Decety, Jeannerod, Durozard & Baverel (1993) showed that imagination of a previously performed foot movement produced a significant increase in breathing frequency and a concomitant fall in end-tidal P_{CO_2}. Their study included non-invasive measurements of intramuscular metabolites (PCr, P_i) and pH during actual and imagined exercise using NMR spectroscopy. No changes were detected during imagination of exercise. Although this method does not indicate to what extent a limited increase in EMG activity could be present during imagination of exercise (Jacobson, 1932), such activity is unlikely to explain the observed changes in ventilation. Decety *et al.* (1993) concluded that the observed increase in ventilation is of 'central origin' since no change in metabolism occurred either systemically or locally in the 'imagined' working muscle. Wang & Morgan (1992) have investigated the effects of using an internal perspective (i.e. from a 'first-person' point of view), as opposed to using an external perspective (i.e. as seen from the 'outside') for the imagination of intermittent elbow flexion against a load. Cardiorespiratory responses were associated with the internal perspective but not with the external perspective. The current study required subjects to perform the imagined exercise from an internal perspective but, unlike the study of Wang & Morgan (1992), specific internal cues were not defined and, in particular, no mention of breathing was included in any instructions to the subjects. Despite this, ventilatory effects reported by these authors are quantitatively smaller but could reflect the different forms of exercise being imagined.

The present study extends the observations made in previous studies by comparing the effects of imagined exercise with those associated with a visualization task (imagined letters) not involving a sense of physical effort. The ventilatory response to imagined exercise, in the athletic group, was significantly greater than that during the imagined-letters task. However, the latter task was associated with some stimulation of ventilation which did not appear to be treadmill-speed related; this is reminiscent of the ventilatory effect associated with a general increase in mental activity such as in response to mental arithmetic, auditory or visual stimuli (Shea, Murphy, Hamilton, Benchetrit & Guz, 1988). The gradual increase in heart rate during imagined exercise observed in the present study was of a similar order to that reported by Decety *et al.* (1991). Since this effect was also found in the imagined-letters control task, it is possible that the increase in heart rate in both studies arose as a non-specific response due to a general increase in mental activity associated with each task.

Volunteered comments and responses to structured interviews suggest that the following factors may be determinants of individual variability of the ventilatory response to imagined exercise: (i) entrainment of respiratory rhythm to a 'memory' of step frequency, (ii) awareness of breathing and its use as an imagination strategy, and (iii) the nature of prior sporting experience. There is little indication from the actual exercise data that substantial entrainment of respiratory rhythm had occurred in the group of athletes. Of the five athletes who indicated that they had timed their breathing with their stepping frequency during actual exercise, a comparison of actual stepping frequency with respiratory frequency approached a ratio of 3 : 1 or 2 : 1 (but never 1 : 1) in only two subjects, the hurdler and the rower. These two subjects were classified as 'weak' and 'non-' responders, respectively. This analysis does not substantiate the suggestion of a mechanism involving a 'memory' of the stepping rhythm during imagined exercise to which respiration becomes 'locked'. This, however, does remain a potential contributing factor particularly since the subjects showing the greatest ventilatory response to imagined exercise (F. H. and P. I.) have an intensely active sporting background involving rhythmic movements. Although in this study, the athletes were asked to comment on their use and awareness of breathing during the actual exercise task, it is not known to what extent breathing awareness or entrainment is part of their usual running technique. It would be interesting to examine more directly the possibility that athletes are more likely to generate a ventilatory response to imagined exercise because, unlike non-athletes, they are usually aware and make 'use' of breathing during running.

Volunteered comments by the subjects can be considered to be the most informative in assessing the subjects' perceptual experiences during imagined exercise. When volunteered comments referring to breathing awareness were made, subjects spoke of a deliberate attempt to reproduce a 'normal exercise breathing pattern' or to mimic the exercise-associated sensation of 'being out of breath and breathing harder'. Such comments raise the possibility that at least part of the observed effects on ventilation may have been volitionally driven. It is interesting to speculate whether the evoked sensorial component from the moving respiratory apparatus or the sense of effort linked with this extra volitional drive may itself improve the ability and/or vividness of the imagination of exercise; breathing may thus be an integral part of the imagination strategy. This notion is supported by the fact that four of the athletes and two of the non-athletes, when directly questioned at the end of their participation, acknowledged that they had used their breathing as an internal cue for the imagination of exercise. However, at least one subject (F. H.) clearly indicated, without prompting, that he was initially surprised by the awareness of increased breathing; this suggests that, at least in that subject, the initial ventilatory response to imagined exercise was not a deliberate act. Such an observation may be analogous to the increase in breathing reported to occur during anticipation of exercise (Tobin *et al.* 1986).

Although volunteered comments provide some information on whether subjects deliberately increased their ventilation during imagined exercise, it is difficult to address this question objectively. It is not easy to explain the lack of reproducibility of the ventilatory response to imagined exercise in some subjects, unless the response is at least, in part, volitional or there is a considerable day-to-day variability in the ability to imagine. A bigger effect on a second occasion could also reflect a 'training effect' on the ventilatory response to imagined exercise. Although not assessed in the present study, it would have been interesting to see how accurately subjects could deliberately 'mimic' the ventilatory response to actual exercise while at rest; this could provide an argument against a purely volitional act as an explanation for the response to imagined exercise, since one might expect a truly volitional act to produce a response which would be closer quantitatively to the ventilatory response to actual exercise. Furthermore, a deliberate increase in breathing might be expected to produce an increase in both respiratory frequency and tidal volume, whereas the observed responses to imagined exercise were almost exclusively due to increased respiratory frequency alone.

The present study also shows that highly trained competitive athletes are more likely to show a significant ventilatory response to imagined exercise. Factors such as the ability to control breathing during physical activities and the use of 'mental practice' (i.e. a visualization of the physical task) in the athletes' training regime may favour a better response. A recent study by Yue & Cole (1993) has shown that a training programme involving the imagination of a repetitive digit muscle contraction task can produce improvements in the force and endurance capacity of the muscle, as does training with actual contractions. Since with 'mental' training, there is no muscular contraction, the improvement in performance is likely to be due to the effects of the training on central mechanisms governing the muscular contraction. Athletes may produce a greater ventilatory response to imagined exercise because their training (both physical and mental) facilitates the central mechanisms involved.

The present study cannot directly address the possibility that neural structures involved in the control of breathing during exercise are responsible for the observed ventilatory effects of imagined exercise. However, insights on the neurophysiological basis of motor imagination have been provided by studies of regional cerebral blood flow (rCBF). In such studies, rCBF provides an index for focal neuronal activity (Raichle, 1987). Although an earlier study by Ingvar & Philipson (1977) showed somewhat different patterns of activation between mental conception and actual execution of clenching the hand, subsequent brain imaging studies tend to support the hypothesis of common neural mechanisms between motor imagery and execution of motor programmes. In general, the supplementary motor area (SMA; Roland, Larsen, Lassen & Skinhoj, 1980; Decety, Philippon & Ingvar, 1988), the cerebellum (Decety *et al.* 1988; Decety, Sjoholm, Ryding, Stenberg & Ingvar, 1990; Ryding, Decety, Sjøholm, Stenberg & Ingvar, 1993) and the basal ganglia (Decety *et al.* 1990; Ryding *et al.* 1993) have been shown to be activated during both imagined and actual motor tasks. The actual execution of the motor task was additionally associated with activation of contralateral primary motor cortex and somatosensory areas. In contrast, the imagination of an outside environment, with the subjects specifically instructed not to imagine their own bodily movements, was associated with activation of a different set of cortical sites including the visual areas (Roland, Erickson, Stone-Elander & Widen, 1987). The SMA, the cerebellum and the basal ganglia shown to be activated during imagined motor tasks are part of the neural network known to be involved in the early stages of motor control (Eccles, 1982). Recent experiments using positron emission tomography (PET) technology have demonstrated that these particular areas are also activated during volitional control of breathing (Colebatch *et al.* 1991) and during actual dynamic exercise (Fink *et al.* 1993); in addition, these studies demonstrated a common activation site in the primary motor cortex. There appears to be a high degree of functional connectivity between these areas and direct pathways between them have been demonstrated in primate brains (Eccles, 1982). Taken together, these specific regions could form the neural basis of a behavioural mechanism for exercise hyperpnoea, which may also be activated to increase breathing by imagination of exercise. Further insights into these mechanisms would benefit from simultaneous brain imaging and ventilatory measurements; the feasibility of such an experiment would depend on the extent to which supine subjects with their head in a PET scanner would be able to imagine dynamic exercise adequately.

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