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Vegetative response during imagined movement is proportional to mental effort

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Measurement of cardiac and respiratory activity during mental simulation of locomotion at increasing speed revealed a covariation of heart rate and pulmonary ventilation with the degree of imagined effort. The degree of vegetative activation of a subject mentally running at 12 km/h was comparable to that of a subject actually walking at 5 km/h. This effect cannot be explained by an increase in peripheral (e.g. muscular) metabolic demands. Indeed, oxygen uptake decreased during motor imagery. This finding is suggestive of a commonality of neural structures responsible for mental imagery of movement and those responsible for programming actual movement. In addition, it provides an quantifiable way of testing mental imagery in relation to movement by using easily accessible biological markers.

INTRODUCTION

There is growing evidence which shows that mental imagery related to movements shares at least part of the mechanisms underlying motor preparation and execution[10]. Experimental arguments as to this point are drawn from several sources. First, the time to perform an action mentally is closely similar to the time needed to actually execute the same action. Experiments using mental scanning of a memorized map, where the subject was required to move mentally from one point to another on the map, showed that the scanning time was linearly related to the distance to be scanned[7]. When mental scanning times were compared with actual scanning times, they were found to be within the same range[5]. This point was directly addressed by Decety et al.[2] in an experiment where actual and mental timing of motor performance were compared in a walking task. Blindfolded subjects were instructed either to actually walk or to imagine themselves walking, to previously inspected targets. In both cases, they triggered a timer on departure and stopped it when they thought they had reached the target. Not only were actual and mental walking times found to increase linearly with target distance, as expected, but they also were found to be virtually identical. Similar data were obtained by Decety and Michel[1] in an experiment comparing actual and mental movement times in a graphic task.

Another set of arguments arises from experiments using cerebral functional mapping techniques, such as the mapping of the regional cerebral blood flow (rCBF). A number of cortical motor areas have been shown by this method to be activated during a mentally imagined sequence of movements, including the premotor areas and the supplementary motor area. This pattern of activation is strikingly similar to that observed during actual execution of the same sequence of movement. The only marked difference between the two situations is that the primary motor cortex is activated only if movements are actually executed[12]. Recently, Decety et al.[3] demonstrated that, in addition to cortical areas, the cerebellum is also substantially activated during motor imagery; the cerebellar metabolism increased by about 20% during simulated tennis playing.

If it is correct, as the above findings suggest, that motor imagery shares neural mechanisms that are also responsible for motor programming, then brain activation during imagined action should be reflected in some way at the level of peripheral effectors. Indeed, the vegetative activation which normally takes place at the onset of exercise or during anticipation of exercise[13] has

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also been found to be present in the condition where exercise is represented mentally[11]. Because vegetative activation may occur in many situations involving cognitive or affective arousal, including mental imagery, it is conjectured that, in order to be considered as a specific effect, the degree of vegetative activation during motor imagery should be proportional to the imagined effort. In order to test the foregoing hypothesis of a commonality of neural structures involved in imagining and in programming actions, an experiment was used that systematically varied the amount of mental effort produced by the subjects.

MATERIALS AND METHODS

Eleven young subjects in good physical condition and used to sport activities (18–26 years old; 2 females, 9 males), were paid for their participation. They were selected on their ability for imagery, as assessed by Sheehan's questionaire[14]. The selected subjects scored an average of 3.2 (S.D., 0.4) for visual imagery and 3.3 (S.D., 0.5) for kinaesthetic imagery (highest score on the scale, 4.0). Each subject came for two sessions separated by a one-week interval. During the first session (actual locomotion session), subjects were placed on a treadmill. Following a 3-min resting period, the treadmill was started and the subjects locomoted for 3 min at 5 km/h, then for 3 min at 8 km/h and finally for 3 min at 12 km/h. During the second session (mental locomotion session), all subjects were placed again on the treadmill. They were blindfolded and wore earphones connected to a portable tape recorder. Following a 3-min resting period, subjects heard through the earphones a record of the noise of the treadmill running at 5 km/h. This record lasted for 3 min. Immediately prior to the treadmill noise, they received taped verbal instructions to 'imagine themselves locomoting at the speed corresponding to the heard noise'. The same was repeated for 8 km/h and for 12 km/h. The presentation of the treadmill noise was intended to help the subjects to carry on the mental imagery task, and to ensure that each condition had the same duration. The control subject, after the 3-min resting period, received the treadmill noise through the earphones without instructions to imagine walking.

During both the actual and the mental locomotion sessions, electrodes were placed on the subject's chest for recording heart rate using a digital electrocardiograph. In addition, a respiratory mask was placed on subject's face during the last 30 s of each condition (e.g. resting, 5 km/h, etc.) for measuring respiratory parameters. These measurements, which were made using a spirometer and Beckman gas analysers, included: pulmonary ventilation (VE) in liters/min; oxygen consumption (VO_2) in liters/min. An index for oxygen uptake (true O_2) (see ref.4), and CO_2 elimination (in % by liter of expired air) were also computed.

RESULTS

The main finding in this experiment was that both heart rate and pulmonary ventilation increased during the mental imagery of locomotion, proportional to the imagined walking speed. Concerning heart rate, a

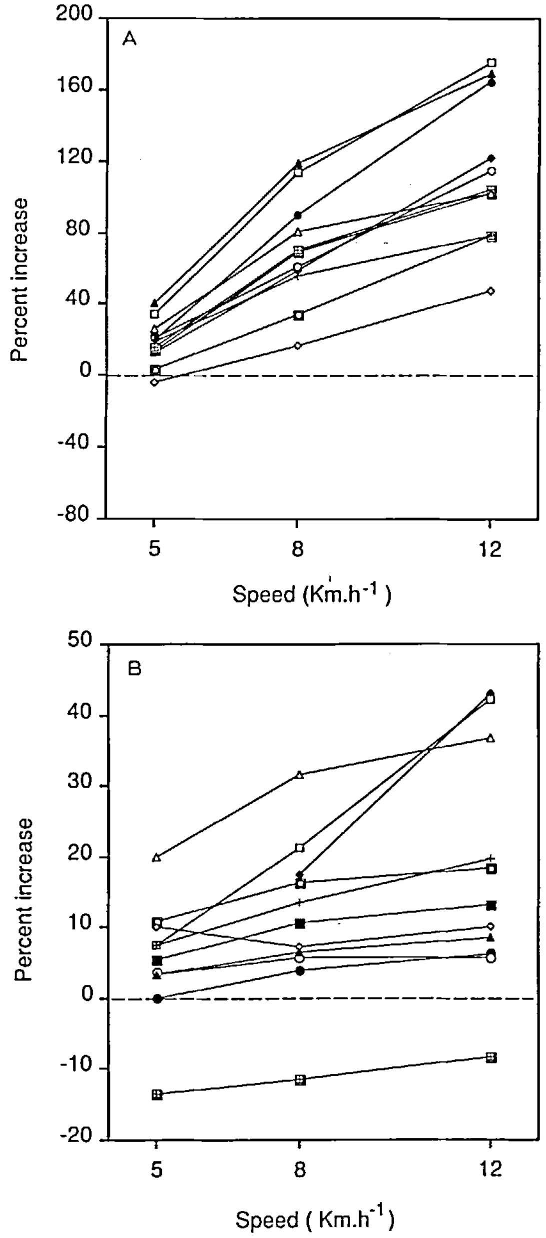

Fig. 1. Increase in heart rate during actual (A) and mental (B) effort, as a function of speed, in the 11 subjects. Values are expressed in percent of resting value. The control subject (below the zero line in B) had a decrease in heart rate during the mental locomotion session.

monotonic increase was observed, which correlated positively with the speed of imagined walking ($r = 0.39$, $P < 0.009$). The mean heart rate was 84.8/min (S.D., 14.0) in the resting condition and was raised to 101.3/min (S.D., 17.0) during the 12 km/h condition. The rate of increase of the frequency of heart beats during the mental locomotion session was about 1.4 beat/min per km/h, as compared with the rate of increase of 7.5 beats/min per km/h observed during the actual locomotion session (Fig. 1A). This effect of imagined speed on heart rate was present in the 10 subjects who passed the mental locomotion session (Fig. 1B). In the control subject, no increase in heart rate was observed: on the contrary, the heart rate tended to be lower during exposure to the treadmill noise than at rest (Fig. 1B).

The analysis of changes in respiratory parameters during the mental locomotion session first revealed an increase in VE. As shown by Fig. 2, the mean VE increased from 9.5 (S.D. 2.9) l/min in the resting condition, to 19.5 (S.D., 10.2) l/min in the 12 km/h condition. A highly significant correlation was found between VE and imagined speed ($r = 0.47$, $P < 0.001$). This increase in VE corresponded to a rate of increase of 0.83 l/min per km/h, as compared to the value of 5.1 l/min per km/h observed during actual locomotion.

The increase of VE during mental locomotion was accompanied by a small but consistent increase in oxygen consumption (VO_2), which also correlated positively with walking speed ($r = 0.44$, $P < 0.005$). It was observed that VO_2 increased from 0.26 (S.D., 0.05) l/min at rest, up to 0.36 (S.D., 0.07) l/min at 12 km/h. By comparison, during actual locomotion, VO_2 increased from 0.33 (S.D., 0.10) l/min to 2.83 (S.D., 0.43) l/min (Fig. 3).

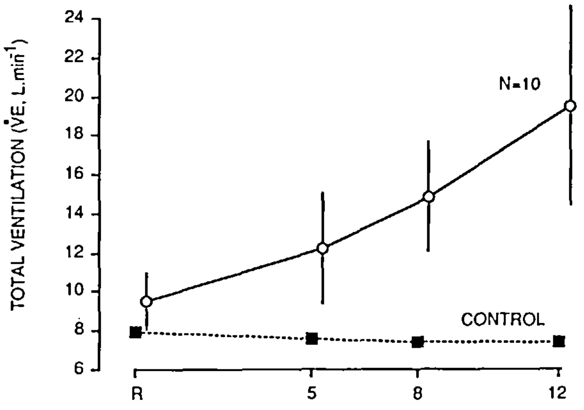

Fig. 2. Mean increase in total ventilation (VE, in liters per minute), as a function of imagined locomotory speed in the 11 subjects. Open circles, mean value of VE for each condition. R, resting condition. Vertical bars represent one standard deviation. Black squares, values of VE in one control subject who was exposed to the noise of the treadmill running at different speeds without being given any instruction for mental imagery of locomotion.

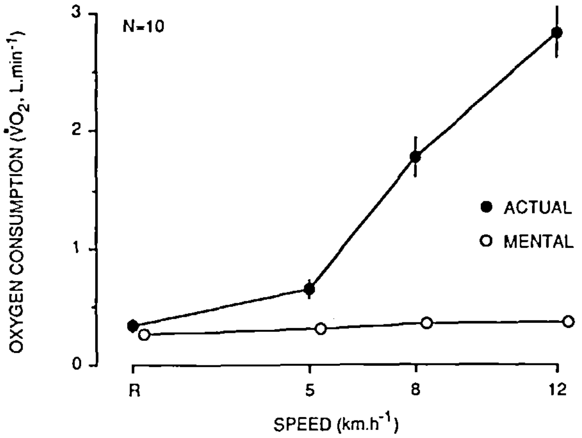

Fig. 3. Comparison of oxygen consumption (VO_2, in liters per minute) during actual and mental locomotion. Filled circles, mean values of VO_2 for the 11 subjects during the resting condition (R) and locomotion at 5, 8 and 12 km/h. Open circles, values of VO_2 for the same 11 subjects during the resting condition and mentally simulated locomotion at 5, 8, and 12 km/h. Vertical bars represent one standard deviation. Note little change in oxygen consumption during the mental conditions.

As a consequence of the disparity between the increase in VE and the less important increase in VO_2 in the mental condition, the oxygen uptake (true O_2) decreased as a function of imagined locomotion speed, such that the estimated proportion of oxygen per liter of expired air during the resting condition (3.70%), dropped to 2.66% during the 12 km/h condition ($P < 0.009$). By contrast, during actual locomotion, the

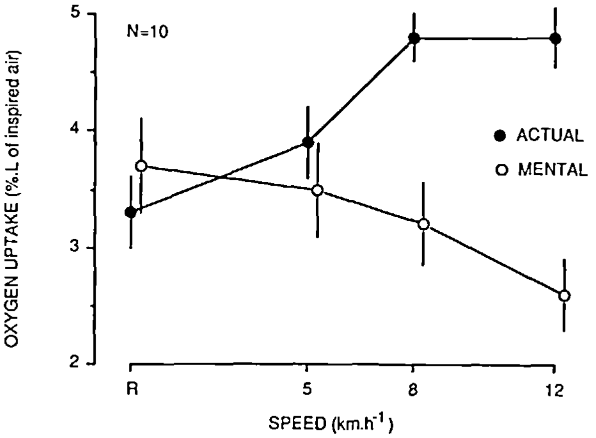

Fig. 4. Comparison of changes in oxygen uptake during actual and mental locomotion in the 11 subjects. Filled circles, values of parameter true O_2 (in percent by liter of inspired air) during actual locomotion, as a function of locomotory speed (R, resting condition). Open circles, values of parameter true O_2 during mental simulation of locomotion, as a function of imagined speed. Vertical bars represent one standard deviation. Note decrease in oxygen uptake in the mental condition, due to increase in total ventilation and correlative stability of oxygen consumption.

oxygen uptake was increased from 3.32% at rest up to 4.74% at 12 km/h ($P < 0.0001$) (Fig. 4). The same effect was observed with CO_2, which showed a decrease in expired air as a function of imagined speed during the mental session (from 3.3% per liter at rest, down to 2.3% at 12 km/h), although it increased during the actual session (from 2.7% at rest, up to 4.6% at 12 km/h).

Finally, in the control subject, VE (Fig. 3), as well as oxygen uptake and CO_2 elimination remained unchanged during the control mental session.

DISCUSSION

Vegetative changes, including increase in heart rate and respiration, have often been reported during situations of mental imagery where psychogenic and emotional factors are manipulated. In such situations the conceptual content processed during imagery (e.g. fear) and the vividness of the image determine the amplitude and pattern of this coincident efferent activity[8,9]. As a possible explanation for this effect, it has been proposed that cognitive or affective arousal could involve a global increase in muscle tone, hence producing an increase in metabolic demands.

The positive correlation between the degree of mental effort and the amplitude of vegetative changes also raises the same problem of a possible increase in metabolic demands during motor imagery. It could be that the subjects, in imagining running at increasing speeds, produced a proportional increase in muscular activity by co-contracting antagonist muscle groups. This explanation, which would account for the increase in oxygen consumption that was observed in the mental condition, cannot be ruled out without a direct measurement of muscular activity (such as EMG) or, even better, a direct measurement of muscular metabolism, such as NMR spectroscopy. However, a closer inspection of the present results reveals a discrepancy between the degree of vegetative activation and the change in oxygen consumption. Indeed, if the increase in oxygen consumption corresponded solely to an increase in peripheral metabolic demands due to muscular contraction, the oxygen uptake should also increase, as is the case during actual physical effort. Our results clearly show that, instead, oxygen uptake decreased during mental effort.

This finding demonstrates that the vegetative activation during motor imagery is greater than required by the increase in metabolic demands and, therefore, that a significant fraction of this vegetative activation has to be of a central origin. Physiological evidence from experiments where respiratory activity was measured in decorticated cats[6] lends further support to these results. Decorticate preparations present long episodes of spontaneous walking movements, which may even persist when the animal is completely paralyzed by curarisation. In this situation, where 'fictive' walking movements can be measured by monitoring the activity of locomotory nerves, there is no muscular contraction and therefore no increase in metabolic needs; nevertheless, the respiratory activity (as measured by monitoring activity of the phrenic nerve) increases in proportion of locomotory activity. This situation bears some resemblance with mental locomotion in our subjects where motor output was also blocked during 'fictive', or imagined, walking movements.

The fact that vegetative activity during mental effort increases beyond the level of metabolic demands supports our initial hypothesis of a commonality of mechanisms between actual and imagined action. This effect can be considered as a vegetative response pertaining to the normal pattern of activation which occurs during motor programming. In this way the central programming structures would anticipate the need for energetic mobilization required by the planned movement to the same extent as they anticipate the amount of activity needed in the motor pathways for producing the movement.

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