A COGNITIVE APPROACH TO PHYSICAL EXERCISE AND SPORT

GIULIANO FONTANI AND SILVIA MIGLIORINI

Department of Physiology, University of Siena

ABSTRACT

This paper summarizes some of the results obtained by our group at the Institute of Physiology in Siena where, in the 1970s, Giancarlo Carli founded the School of Sports Medicine. Carli inculcated a deep interest in the relation between cognition and physical activity in students and colleagues. The main focus of our work were the cognitive factors able to influence sport performance, their neurophysiological correlates, the effects of physical and mental training on performance, and the relation between nutrition and physical/cognitive activity. We have shown that: (a) training reduces reaction times, errors, and variability in the performance of attentional tasks; (b) the characteristics of the motor action and of the related motor cortex potential is modified by both physical and mental imagery training; (c) dietary supplementation with omega-3 fatty acids and policosanols improves reactivity and attention, modifies the profile of mood states, and induces changes in the cerebral activity associated with motor action, similar to those observed after physical training; and (d) the glycaemic index of foods is associated with specific levels of cognitive performance relevant to physical activity. We are grateful to Professor Carli to have oriented our interests, encouraged our research, and helped us with his enthusiasm and criticism.

Key words: attention, reaction time, movement-related brain macropotentials, mental imagery, omega-3

Giancarlo Carli has always been interested in sports and, in his teens, he had planned to become a coach. In fact, he became a Professor of Physiology and, in the late 1970s, founded the Graduate School in Sports Medicine at the Institute of Physiology of the University of Siena and created a line of research that, over the years, has produced interesting results and educated several talented professionals in sports medicine. His group research focused on the activity of hormonal changes occurring during exercise and on the functional evaluation of athletes. In this context, his friendship and collaboration with the founder of Also Enervit, Paolo Sorbini, was very important. Indeed, they shared a curiosity and enthusiasm for sports and physical exercise, and in the development of appropriate nutritional strategies for athletes. Their aim was discouraging the use of doping in sport, studying athletes' performance during competition, and giving laboratory support to field tests.

During the 1970s, Giuliano Fontani was engaged with Carli in the study of the neurophysiological correlates of attention and emotion in freely moving animals in an open field model. Thus, when Fontani moved into sports research, he started with studies on the

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neurophysiological effects induced by physical activity and training. Professor Carli encouraged him to transfer his laboratory experience concerning attention and emotion in animal models to sport applied physiology, as these aspects might be relevant in improving athletes' performance.

THE INFLUENCE OF PHYSICAL AND MENTAL TRAINING ON MOTOR ACTION REACTIVITY AND NEUROPHYSIOLOGICAL CORRELATES

At that time, standardized protocols for physical training had already been adopted by top level athletes (Fontani et al., 2006). In contrast, the cognitive-emotional factors possibly affecting performance had not been systematically addressed, although many strategies aimed at improving skilled movements, not only by means of the practice of motor execution (Yan & Dick, 2006) but also by mental representations of the motor task (Solodkin et al., 2004) were being developed.

Our aim was to study the physiological variables relating to the psychological aspects of performance and their changes after mental training (Fontani et al., 1999; Fontani & Lodi, 2002). Specific indices of brain activity, such as event-related potentials (ERP) are associated with motor preparation and execution, and some electrical brain potentials are closely related to movement (Kornhuber & Deecke, 1965; Shibasaki et al., 1980) and to skilled motor activities (Papakostopoulos, 1978; Fattapposta et al. 1996; Fontani et al., 2001). Learning modifies these profiles.

A sequence of brain potentials, movement-related brain macropotentials (MRBMs), occurs in relation to the execution of skilled movements (see Figure 1) (Chiarenza, 1991; Fattapposta, et al., 1996). MRBMs have been observed during the performance of skilled tasks in both normal developmental and pathological conditions (Chiarenza et al., 1983; Chiarenza, 1986) and have been studied in trained and untrained subjects, where differences have been described as a consequence of long-term practice (Fattapposta et al., 1996; Di Russo et al., 2005).

Specific components of MRBMs occur during pre-motor, motor, and post-motor periods. In particular, a negative phase potential called *Bereitschaftspotential* (BP, readiness potential) has been recorded in the pre-motor period (Kornhuber & Deecke, 1965). This potential reflects various motor and non-motor neural processes linked to motor preparation (Brunia, 1988; van Boxtel & Brunia, 1994); it has been widely studied, but the results are controversial. In some cases, a reduction of *Bereitschafspotential* amplitude was described in association with the uninterrupted repetition of motor activities (Kristeva, 1977) and with improved performance (Fattapposta et al., 1996). In other studies, the BP amplitude was found to increase after acquisition of a skilled motor task (Taylor, 1978), by paying attention to the movement (Grunewald & Grunewald-Zuberbier, 1983), by the high level of preparation required for complex sequences of voluntary movements (Papakostopoulos, 1978; Kristeva, 1984). In the motor period, a pre-motion positive wave followed by a number of waves related to the onset and execution of the movement has been described (Deecke et al., 1969) (see Figure 1).

In particular, the motor cortex potential (MCP), a negative potential occurring in the earliest part of the motor period, has been considered an index of response-generated re-afferent activity from muscles (Papakostopoulos et al., 1975) and is affected by practice (Fattapposta, et al., 1996). Less is known about the other waves recorded during the motor period. N1 has been described as a motor component and P2, recorded during the motor completion period,

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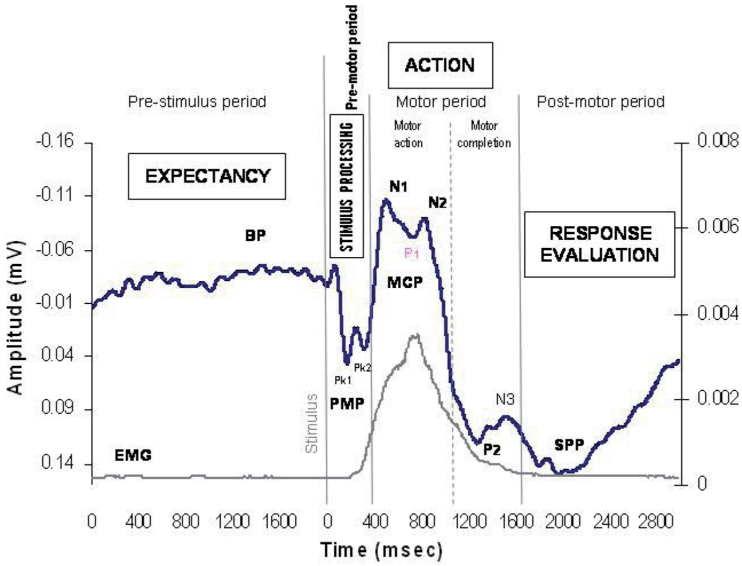

Figure 1. Movement Related Brain Macropotentials (MRBMs) recorded before and after the imperative stimulus

as a somatosensory component (Chiarenza, 1991), while skilled performance positivity (SPP), a positive wave occurring in the post-motor period, seems to increase with the accuracy of the performance (Papakostopoulos, 1978). Despite some doubts in the interpretation of these potentials (Chiarenza, 1991), they can be considered interesting markers of movement, particularly of skilled motor actions, and can be used to monitor the cerebral effects induced by training.

One of our earliest studies was aimed at evaluating the MRBM waveform modifications possibly occurring in correspondence with a finger movement produced to press sequences of keys during attentional tasks. Three groups of subjects were enrolled in the study. One of them performed a simple reaction time test (Alert test, A), in which the subjects had to press three keys of a keyboard in a precise sequence when a figure appeared on the computer monitor. The second group performed a Choice test (CH), a complex reaction time test, in which the participants had to press the three keys in a different order when one of two different figures appeared randomly on the screen. The third group of subjects performed the Choice test with the addition of a Go/No-Go paradigm (CHNG) in which participants had also to repress an unsuitable response. All subjects were tested before and after 10 days of training on the three tests. Electroencephalography (EEG) and electromyography (EMG) were recorded during the tasks.

The results of this experiment led to the conclusion that a short lasting period of training of a motor action had not only effects on the execution of movement, but also on the associated MRBM profiles. The effects were more pronounced on the Choice and Choice + No-Go tests.

The profiles of MRBMs recorded during the Alert test differed from those observed during CH and CHNG tests, as peak latencies and wave durations occurred earlier in A. Differences between CH and CHNG, which require complex central signal processing and high mental effort, were less evident and occurred only in the pre-motor period. The different profiles of the brainwaves recorded during various motor reactions showed a close relationship between the complexity of the task and the electro-cortical activity (Fontani, Migliorini et al., 2009).

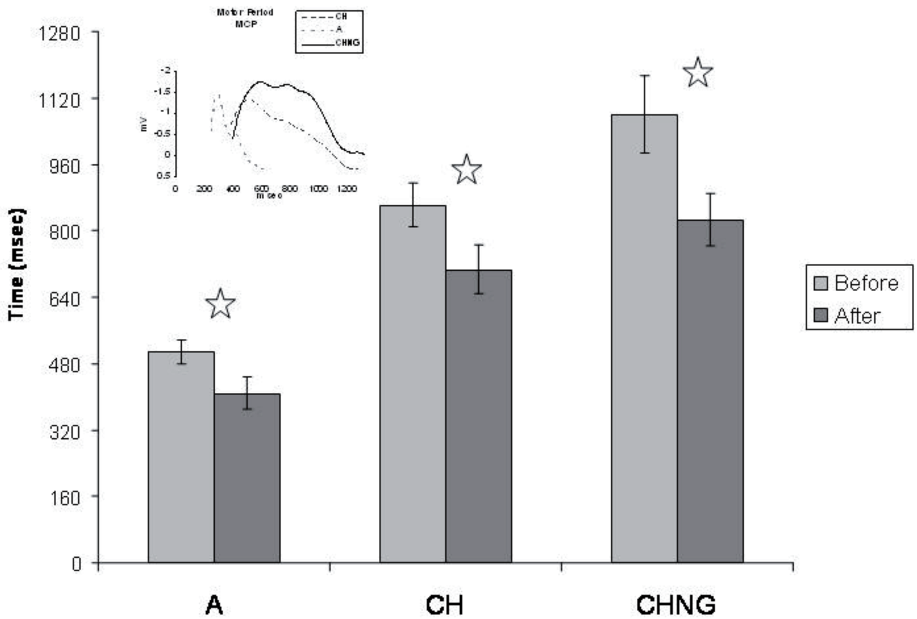

Figure 2. Effect of training on MCP duration. Alert test (A), Choice (CH), and Choice + No-Go (CHNG) tests

After training, reaction times (RTs) and their variability were reduced in both the CH and CHNG tests, while no training effect was observed in test A. The main change in MRBMs was observed in the motor period. It concerned the MCP duration which was reduced in A, CH, and CHNG (see Figure 2). The pre-motor period showed a significant reduction of pre-motor potential (PMP) duration only in the CHNG test. Moreover, the correlations between the MRBMs recorded in the three tests (A, CH, and CHNG) and reactivity (measured by EMG latency and RTs) showed that the PMP duration was the best predictor of the latency and duration of the brainwaves related to the same motor action. This suggested that MRBM waves are strictly related to the motor action.

The results confirmed that the effects of training were more pronounced in the tests involving complex central processing (Fontani et al., 2007). The main effects of training on MRBMs concerned the waves recorded after the presentation of the imperative stimulus (the last stimulus requiring the response), and consisted of a reduction of the latency of the peaks occurring during the pre-motor, motor, and post-motor period. The amplitude of BP, a wave recorded before the imperative stimulus, increased after training, which is in line with earlier studies describing an increase of BP amplitude after acquisition of a skilled motor task (Taylor, 1978)

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and can be due to enhanced attention (Grunewald & Grunewald-Zuberbier, 1983) or to the high level of motor preparation required by the task (Papakostopoulos, 1978; Kristeva, 1984).

The PMP duration seems to be crucial for the duration and latency of the successive waves. This pre-motion positivity occurring after the imperative stimulus probably reflects stimulus processing and the development of motor strategies able to react to the presented stimuli (Deecke et al., 1969; Fontani et al., 2007). Thus, it could be suggested that training reduces the time of central processing via a direct action on the central nervous system (Fontani, Migliorini et al., 2009). This is supported by the reduction of the PMP duration in the CHNG test and may indicate that the effects of training are more pronounced on more complex tasks. Altogether, the results show that training reduces the time of motor cortical elaboration of the stimulus and quickens the transfer of motor action to muscles.

MENTAL IMAGERY AND DEVELOPMENT OF SKILLED MOTOR ACTIONS

The above reported results indicate that MRBMs can be used as indicators of motor learning induced by training. MRBMs can be modified also by the mental representation of skilled motor acts (Solodkin et al., 2004) and a number of studies have shown that mental imagery of a motor action improves the motor skill acquisition (Corbin, 1972; Feltz & Landers, 1983; Roure et al., 1998; Brouziyne & Molinaro, 2005; Driediger et al., 2006). The effects of mental imagery training are similar to those obtained by physical training, both of which could be explained in terms of variation of motor cortex neurons activity (Pascual-Leone et al., 1995). Mental imagery affects not only the motor act, but also muscle strength and trophism, thereby raising prospects for the use of mental imagery in the field of rehabilitation (Jackson et al., 2001). The imagery-induced increase in muscle strength is associated with variations of brain activity (Naito & Matsumura, 1994; Ranganathan et al., 2004) which, in turn, is dependent on psychological factors (Masaki et al., 1998; Ranganathan et al., 2004).

In order to assess the relationship between muscle performance, cerebral variables, and psychological factors, and to evaluate the possible role of mental imagery in sport, we designed an experiment aimed at comparing the effects of three different conditions (no training, active training, and imagined training) on learning a skilled motor ability such as a karate action. In particular, we analysed the influences of motor execution and motor imagery training on brain and muscle activity according to the hypothesis that motor imagery could affect these physiological functions (Fontani, Migliorini et al., 2009).

We studied three groups of athletes who had to learn a new motor action (Ura-Shuto-Uchi): Untrained (subjects not performing any training, UT), Action Trained (subjects performing Ura-Shuto-Uchi training daily for 16 minutes, AT), and Mental Imagery (subjects performing mental imagery training of Ura-Shuto-Uchi daily for 16 minutes, MI). The subjects were tested five times, once every seven days. During each test, they performed a series of 60 motor action trials. In Tests 1, 3 and 5, they also performed a series of 60 mental imagery trials. During the trials, EEG, EMG, muscle strength, and power were recorded.

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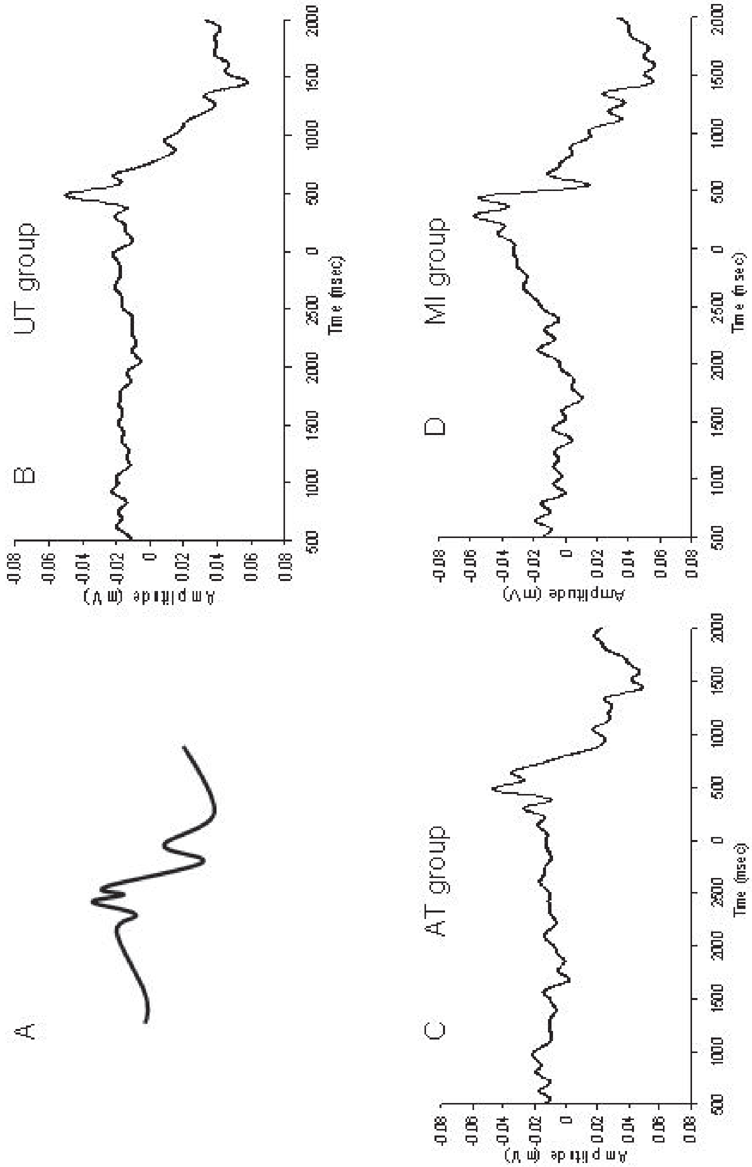

Figure 3: MRBMs in Untrained (UT), Action (AT), and Mental Imagery trained (MI) groups

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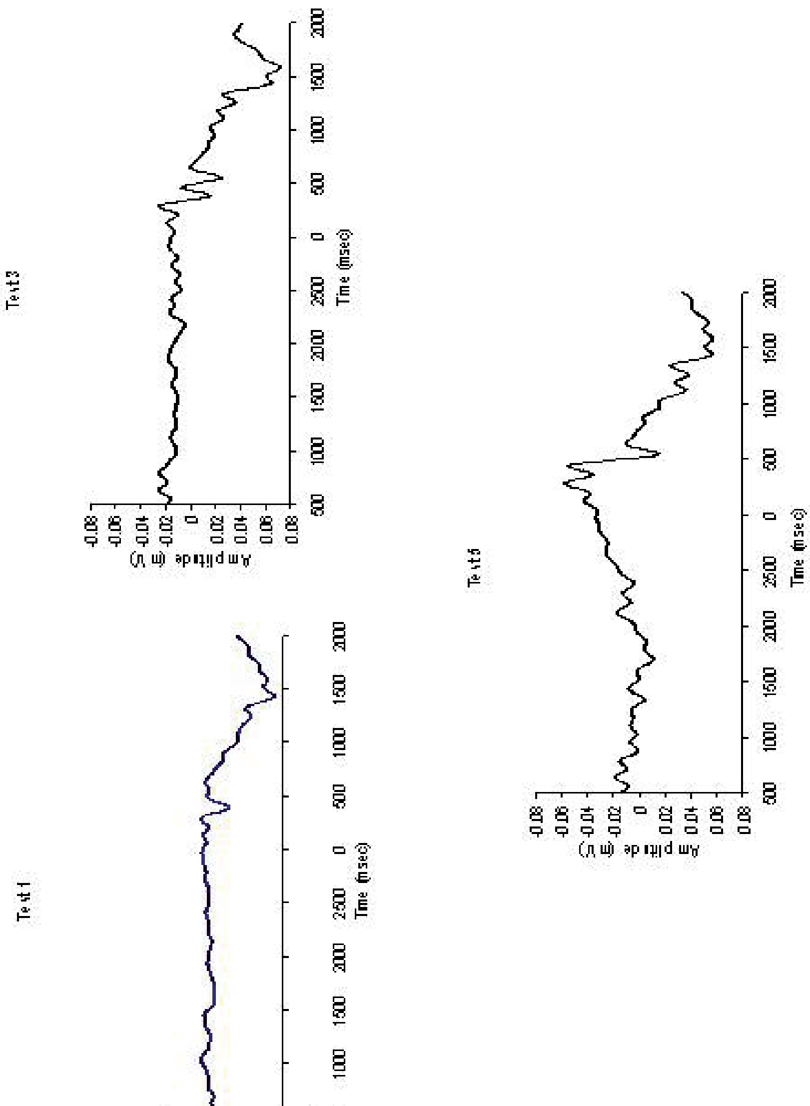

Figure 4: Mental Imagery group. MRBMs recorded at Cz during Tests 1, 3, and 5

Figure 3 shows a MRBMs profile in expert subjects (A) and the profiles of untrained (UT), action trained (AT) and mental imagery trained (MI) subjects, recorded during Test 5.

The UT subjects did not show significant difference over time. In the AT group, training reduced the EMG activation and reaction times calculated at the time of completion of the action. Moreover, muscle strength and power increased significantly. The MI group showed similar effects on muscle strength and power, but did not exhibit changes in reaction times. In this group, the study of MRBMs indicated a progressive modification of the profile of the waves from Test 1 to Test 5 during imagery, with significant variations of the amplitude of the waves related to the pre-motor and motor execution periods. In line with other authors' findings (Ranganathan et al., 2004), we concluded that mental imagery of a motor action modulates the activity of the neural and muscular structures involved in the motor action. Moreover, our results showed that the effects obtained by the AT and MI groups on muscle strength and power were similar. Analysis of the cerebral activity showed that there was a clear modification of the profile of the waves from Test 1 to Test 5 in the MI group, with significant variations of the amplitude of some peaks (see Figure 4). In particular, mental training increased the negativity of the BP, MCP, and N1 amplitudes. The increase in the negativity of BP, a wave occurring before the imperative stimulus, was correlated with the amplitude of PMP and N1, waves occurring after the stimulus in the first motor period, the motor sensory period. The increase of the N1–P2 interval amplitude was particularly evident at Test 5 with respect to Test 1 at Cz and Fz, correspondent to brain areas where the motor processing waves are best represented. The MCP increase was also in line with other reports indicating higher MCP amplitudes in self-paced skilled movements and no change in subjects with learning disabilities (Chiarenza et al., 1983; Fontani et al., 2007). Nevertheless, a few differences in the effects of motor and mental training on the cerebral correlated motor action were present. They can be summarized as less pronounced increase of the amplitude of the waves occurring during the pre-motor period and the motor period, in particular MCP and N1–P2 in the MI group.

In conclusion, mental imagery can be a useful method to learn and to train skilled motor actions. It can be used to build and consolidate motor sequences and to improve muscular capacities, and can be a valid strategy in sport disciplines, particularly those based on specific skilled technical actions (Fontani et al., 2007). In addition, the changes induced in the brain potentials profiles during training allow us to evaluate the effects of motor imagery and monitor the progressive development of a skilled motor action.

COGNITIVE EFFECTS OF DIETARY SUPPLEMENTATION: OMEGA-3 AND POLICOSANOLS

In the perspective of the relation between nutrition and physical activity, another research line that we developed across the years concerns the effects of food supplements on cognitive functions. In particular, we have shown that, in healthy subjects, dietary supplementation with omega-3 fatty acids and policosanols improves reactivity and attention as well as mood states and emotional control (Fontani, Lodi et al., 2009), while we failed to detect omega-3 induced effects on motor-related brain potentials. Our results on attention and reactivity are in line with the current literature showing that omega-3 fatty acids may play a role in cognitive development (Jho et al., 2004), increase learning ability (Neuringer et al., 1994; Sears, 2002), and improve cognitive performance (Willatts, 2002). The omega-3 efficacy on cognitive performance is associated with many beneficial effects: they are considered an important anti-inflammatory factor (Yehuda et al., 2002), show inhibitory effects on tumorigenesis, and reduce mortality from cardiovascular diseases (Fletcher & Ziboh, 1990; Piomelli 1994; Yehuda et al., 2002; Fontani, Corradeschi, Felici, Alfatti, Bugarini et al., 2005; Corradeschi et al., 2006). Omega-3 fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are manufactured in the body using alpha-linolenic acid as a starting point (Arita et al., 2003). In the nervous system, polyunsaturated fatty acids are released from membrane phospholipids when neurones are stimulated by neurotransmitters and are locally metabolized, giving rise to a series of active products, such as the eicosanoids, which may act in the intracellular environment as neuronal second messengers and influence neuromodulation, synaptogenesis (Haag, 2003), synaptic plasticity (Martin & Bazan, 1992), and signal transduction (Jones et al., 1997). In particular, they are involved in cholinergic, serotoninergic, and catecholaminergic synaptic transmission (Piomelli et al., 1991; Horrobin et al., 2002; Haag, 2003).

In other experiments (Fontani et al., 2000), we observed that policosanols, a mixture of higher aliphatic primary alcohols derived from wheatgerm oil and sugarcane wax which can lower blood cholesterol levels (Larsson et al., 2004), can reduce reaction time in attention tests and affect some event-related brain potentials, increasing their amplitude and reducing the latency of some peaks, as previously observed (Lòpez & Ortega, 2003). From these experiments, we can infer that event-related potentials are influenced by omega-3 and policosanol.

Since policosanol and omega-3 have similar effects on reaction time and related brain activity, we hypothesized that the association between policosanols (P) and omega-3 (O-3) could affect reactivity in simple and/or sustained attention tests and modify the profiles of MRBMs. Thus, we carried out a study including conditions requiring prolonged high levels of mental engagement. In this study, complex reactions in subjects (karateka) trained to react quickly and with precise motor sequences to sudden stimuli have shown that after 21 days of dietary supplementation (Test 2 vs. Test 1 performed before O-3 and P supplementation), the subjects reduced their reaction times and increased the vigour sensation while decreasing the scores of anger, anxiety, fatigue, confusion, and depression measured by the POMS (Profile of Mood States) test.

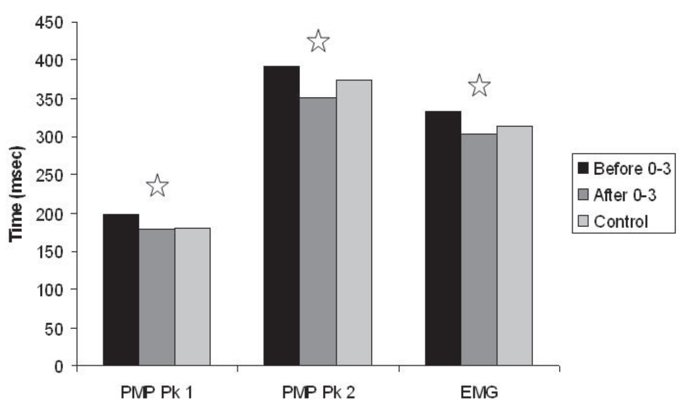

Figure 5: Latency of PMP (Pre-Motor Potential: Pk1, first peak and Pk2, second peak) and EMG recorded before and after omega-3 supplementation and during control period

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Analysis of the event-related brain potentials showed a reduced latency of MRBMs. In particular, the potentials recorded in the pre-motor period and motor period occurred earlier and the latency of EMG activation was reduced (see Figure 5). After a further 21 days from the last O-3 + P supplementation (Test 3), the positive effects on the mood state persisted, while the reaction time, EMG, and brain potential latencies increased, although their values remained at lower levels than in the first test. The placebo group did not show any significant differences in Tests 2 and 3 with respect to Test 1 for either POMS or reactivity and brain potentials. These results confirm our previous experiments (Fontani, Lodi et al., 2009) in which omega-3 and policosanols affected reactivity and neurophysiological measures and are in line with similar experimental approaches (Stoll et al., 1999; Lòpez & Ortega, 2003; Savva et al., 2004; Fontani, Corradeschi, Felici, Alfatti, Migliorini et al., 2005). Policosanols reduce reaction time in simple go/no-go and choice attention tests and reduce the latency of the event-related potentials after the stimulus (Lòpez & Ortega, 2003). Omega-3 polyunsaturated fatty acids improve mood profile and reduce reaction time in complex attention tests, particularly those involving the go/no-go paradigm, while the effects on the event-related potentials are limited to an increase of amplitude of the waves occurring before and after the stimulus during the go/no-go test (Savva et al., 2004; Fontani, Lodi et al., 2009).

The omega-3 induced variation of cerebral waves related to movement strengthens the hypothesis of a direct action of omega-3 fatty acids and policosanol on the central nervous system (Fontani, Lodi et al., 2009). The mechanisms involved may be related to omega-3 acting as a controller of neuronal excitability (Puri et al., 2004) and modulating many of the signal transduction mechanisms operating at the synaptic level (Haag, 2003), while policosanol can facilitate membrane conductivity (Lòpez & Ortega, 2003; Peet & Stokes, 2005), matching some of the effects of omega-3 and being particularly effective on reactivity (Lòpez & Ortega, 2003).

GLYCAEMIC INDEX AND ATTENTIONAL CAPACITY

Another important parameter related to the capacity to maintain and improve attention during physical activities characterized by a high commitment of attention is the blood glucose level. This variable should be kept constant, as glucose is the main energy source for the brain and adequate blood levels of carbohydrate are necessary for the maintenance of optimal cognitive function (Ciok & Dolna., 2006; Nilsson et al., 2009). The speed with which it is transported from food to blood is a function of the glycaemic index (Scholey et al., 2001; Benton et al., 2003).

The concept of the glycaemic index (GI) was introduced in 1981 by Jenkins and colleagues (1981) and is widely recognized as a reliable method to predict the rise of blood glucose caused by various foods and, consequently, the associated rising of blood insulin (McLaren, 2000; Foster-Powell et al., 2002; O'Reilly et al., 2010).

Many studies have shown that, compared to placebo, an increase in glucose is associated with better cognitive performance, both in humans and animals (Kaplan et al., 2000; Park, 2001; Benton et al., 2003; Flint & Turek, 2003; Lieberman, 2003; Ingwersen et al., 2007; Gilsenan et al., 2009; Nilsson et al., 2009). Although the evidence is not always consistent, there is evidence that carbohydrate ingestion may improve concentration, reaction times, learning ability, mood, memory, and psychomotor performance; likewise, an insufficient glu-

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cose supply causes a worsening of these skills/tasks (Ciok & Dolna, 2006; Scholey et al., 2001; Papanikolaou et al., 2006; Hoyland et al., 2008). Glucose uptake by the brain depends on brain activity and, thus, is also a function of cognitive demand, as shown by the increased glucose metabolism in the brain areas involved in cognitive activities (Hoyland et al., 2008). Several studies have shown that low GI foods, causing a smaller increase in postprandial release of insulin, lead to a lower uptake of glucose by insulin-sensitive tissues such as the muscles, liver, and white adipose tissues that facilitate the flow of glucose from the blood to the brain, allowing the attainment of improved cognitive performance compared to high GI foods (Kaplan et al., 2000; Benton et al., 2003; Ciok & Dolna, 2006; Ingwersen et al., 2007; Gilsenan et al., 2009; Nilsson et al., 2009). This could be particularly important during activities requiring constant high levels of attention, whose decrement is the main symptom of mental fatigue.

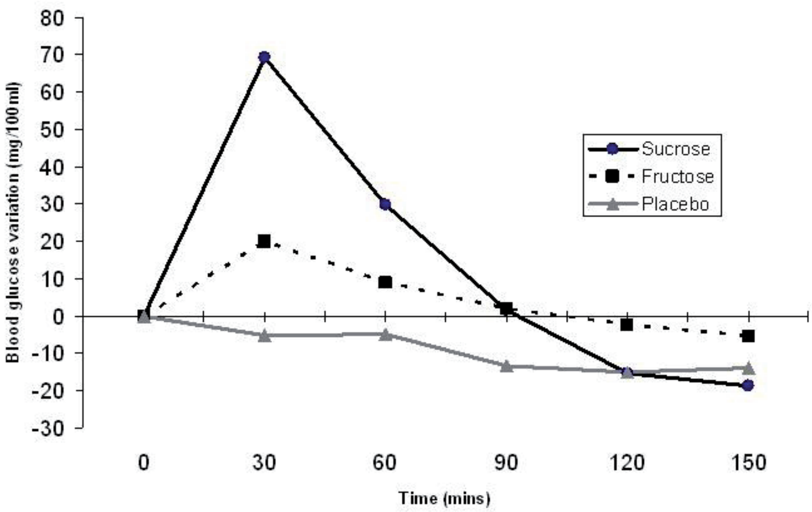

Figure 6: Blood glucose variation. Comparison between sucrose, fructose, and placebo during 150 minutes after intake. Data are presented as variations from the initial value

In a preliminary experiment we studied the variation of attention and related physiological parameters in healthy subjects after intake of carbohydrates of different GI in healthy volunteers. The experimental sessions were held on Day 1, 20, and 40 in which each subject randomly received a solution containing sucrose (high GI), fructose (low GI), and a sweetener (placebo). Blood collections were held at 30, 60, 90, 120, and 150 minutes after solution intake. An attention barrage test, concomitant with EEG recording, was performed at 30, 90, and 150 minutes. The results showed that the average blood glucose levels had different profiles: after sucrose there was an increase of blood glucose, with a peak at 30 minutes, followed by a rapid decrease. Fructose showed a lower increase after 30 minutes and a slow decrease in the

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following minutes, while placebo intake was followed by a slight decrease of blood glucose (see Figure 6). The analysis of the barrage test did not show differences between sucrose and fructose after 30 minutes, but in the following tests, the number of errors was lower in the fructose test. EEG frequency analysis showed an increase of high frequencies after fructose during barrage in the second and third test (Migliorini et al., 2009). These data confirm that the glycaemic index of carbohydrates modulates cognitive performance and that attentional capacity is reduced when blood glucose levels are low. Indeed, the rapid reduction in blood levels of glucose occurring after the initial peak (30 minutes) was accompanied by an equally marked decrease in attentional capacity. Moreover, in agreement with data from other studies (Thomas et al. 1991; Scholey et al. 2001; Ingwersen et al. 2007; Simpson et al. 2007; Nilsson et al. 2009), the results of our experiment showed that the intake of low GI carbohydrates, such as fructose, can counteract the decline in attentional performance and, thus, prevent the effects of mental fatigue. The results of our experiment are further supported by the analysis of EEG frequencies, which showed a marked increase in high frequencies (in particular γ) during performance of attentional tests after fructose intake. This is in agreement with data that showed a strong link between γ EEG frequencies and processes of selective attention: higher levels of the latter are related to an increase of γ waves during EEG recordings (Aoki et al., 1999; Ray et al., 2008). Minor decreases in blood sugar following consumption of low GI carbohydrates, therefore, seem to correspond to high levels of high frequencies and lower levels of low frequencies recorded during performance of attentional tests.

These findings suggest that proper protocols of carbohydrate intake before and during exercise can prevent significant reductions in attentional capacity during competition, which is particularly useful in open skill sports in which high levels of sustained attention are required (Migliorini et al., 2009).

CONCLUSION

Our findings confirm the relevance of cognitive competences and training in physical exercise and sports, and indicate that the original intuition of Giancarlo Carli – the importance of laboratory experiments to support research in many open skill sport disciplines – was valid and is still fruitful.

Our studies on the cognitive factors involved in the improvement of sport performance and on their modulation by psychological and nutritional variables moved from the multifaceted cultural atmosphere we experienced at the Institute of Human Physiology in the 1970s, when the newly founded School of Sport Medicine started its activities. They are a product of our education as neurophysiologists received in Carli's lab and of the interest in cognition that had been a marker of the laboratory since Professor Carli obtained a Chair in Siena. In those years, the main characteristic of the lab was an enthusiastic multidisciplinarity which allowed each of us to develop her/his own talents in research on the physiology of exercise and sport. We are grateful to Giancarlo Carli because he oriented our interests, encouraged our research, and helped us with his criticism and advice. Finally, we have to say that, beyond research, it has also been a pleasure to have had the opportunity to rigorously educate so many medical doctors in sports medicine in the friendly, collaborative, and relaxing context created by Giancarlo Carli.

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Correspondence to Giuliano Fontani, Department of Physiology, University of Siena, Via A. Moro, 4, 53100 Siena, Italy
Email: Giuliano Fontani (giuliano.fontani@unisi.it)
Phone: +39 0577 234035
Fax: +39 0502 34037

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