Sport Benefits on Disabled Athletes' Executive Functions

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Abstract

We investigated the effect of sports activity on physically-disabled individuals using behavioral and electrophysiological techniques. Visual Go/No-go discriminative and simple response task were used. Participants included 17 disabled athletes, 9 from open-skill (wheelchair basketball) and eight from closed-skill (swimming) sports, and 18 healthy non-athletes. Reaction times of disabled athletes were slower than those of healthy non-athletes on both tasks (7% and 13% difference). Intra-individual variation of reaction times, switch cost and number of false alarms were higher in the swimmers but comparable to healthy non-athletes in the basketball group. Event-related potentials (ERPs) early components P1, N1 and P2 had longer latencies in the disabled. The late P3 component had longer latency and smaller amplitude in the disabled only in the discriminative response task. Differently, the N2 component, which reflected inhibition/execution processing in the discriminative response task, was delayed and reduced in the swimmer group but was comparable to healthy subjects in the basketball group. Results show that a) ERPs components related to perceptual processing and late components related to executive processing are impaired in disabled subjects; b) open-skill sports such as basketball may partially compensate for executive control impairment by fostering the stability of motor responses and favoring response flexibility.

keywords: ERPs, physical disability, deafferentation, cortical plasticity.

Current research in many areas (physiology, biology, biomechanics, etc.) reflects interest in the effect of sports activity on individuals with physical disabilities. Although psychological studies are few and mostly focused on psychosocial effects, they show that participation in sports is important for improving perceived quality of life and community integration (e.g. McVeigh et al., 2009) and for benefits on anxiety and depression (e.g. Gioia et al., 2005). As physical activity might also have a positive effect on basic psychomotor functions, we analyzed some basic psychomotor functions and their underlying brain activity in disabled athletes.

Psychomotor functions are impaired in persons confined to a wheelchair following spinal cord injury (SCI), amputation or neural infections, such as poliomyelitis (e.g. Plinta et al., 2005). In a large group of participants, simple and choice reaction times of functionally intact upper limbs to visual stimuli were slower than those of healthy, able-bodied controls. Research on sensory deprivation suggests that loss of somatosensory input to the central nervous system may have an impact on cortical reactivity and subsequent cognitive task efficiency in individuals with SCI (e.g. Crossman, 1996). Few electrophysiological data show that cognitive brain responses to tactile and auditory tasks are attenuated in SCI subjects (Ament et al., 1995; Choen et al., 1996); moreover, P3 components to visual stimuli have longer latencies than normal in amputees (Karl et al., 2004).

Studies in healthy athletes show that extensive daily physical training modifies cortical activity (for reviews, see Hatfield and Hillman, 2001; Nakata et al., 2010). Neural efficiency (*i.e*. the same work performed with less cortical effort) has been shown in athletes using electrophysiological techniques. However, the reverse effect, *i.e.*, enhanced cortical activity in athletes with respect to controls, has been reported in sensory stimuli processing (Özmerdivenli et al. 2008; Murakami et al., 2008) and when attention and motor inhibition are required (Di Russo et al., 2006). These data can be interpreted as adaptive changes consequent to sports activity. In agreement with the neural efficiency theory, motor preparation requires less cortical activity (Di Russo et al., 2005a,b); however, enhancement of sensory and cognitive event-related potential (ERP) components is consistent with top-down attentional modulation of input and output associated with excellent performance on specific tasks. Although the effect of sports on the brain is well documented in healthy athletes, no data are available on disabled athletes.

As different sports activities require different sets of skills, we selected two sports that require very different cognitive (especially executive[1]) skills, *i.e.*, basketball and swimming. Sports such as basketball (or fencing, football, hockey etc) usually involve "open-skills" because the environment constantly changes and movements have to be continually adapted. These skills are predominantly perceptual and externally paced (e.g. a pass in basketball). By contrast, "closed-skill" sports, like swimming, archery and golf, take place in a stable, predictable environment, and the performer knows exactly what to do and when. Therefore, skills are not affected by the environment and tend to be habitual. Movements follow set patterns and have a clear beginning and end. Skills tend to be self-paced (e.g. swimming, shooting sports, archery and golf).

We used a Go/No-go task that required typical open-skill sports skills. This task mimics some of the complexity of the visual motor behavior of basketball players. The latter have to respond to the opponent's actions and often to switch from an intended action to a new one that is more appropriate for the changing situation. In the Go/No-go task, the subject has to produce a fast motor response to target stimuli and to refrain from responding to other non-target stimuli. This paradigm involves many perceptual, cognitive and motor processing stages: a) task preparation, during which the relevant task-set is activated (in the present experiment: "prepare to discriminate among several stimuli"); b) stimulus perception and identification; c) stimulus response mapping, *i.e.*, selecting stimulus category and mapping to the assigned response; d) response execution or response inhibition; e) response monitoring (error vs. correct response) and adjustment of attention. Besides their relevance in open-skill sports, these processes underlie the ability to cope fast and appropriately with the changing environment in everyday life (e.g. when driving, switching from the accelerator to the brakes at a red light).

Different experimental conditions (i.e. discrimination difficulty; multiple motor response choices; occurrence probability of Go and No-go trials) modulate the processing load in the various stages of the Go/No-go task. In accordance with the literature, to focus on motor execution and inhibition (rather than interference, conflict or error processing), we used equal probability of Go and No-go stimuli occurrence. The task required relatively simple feature

1 Executive processes are responsible for planning, cognitive flexibility, abstract thinking, rule acquisition, initiating appropriate actions and inhibiting inappropriate actions, and selecting relevant sensory information (Stuss et al. 2003).

discrimination (targets vs. non-targets); moreover, single motor responses had to be made (Go trials) or withheld (No-go trials). In another experiment, we used a simple reaction task in which stimulus discrimination was not required and the participants had to press a key at the appearance of all visual stimuli.

Relevant information on the neural mechanisms underlying performance can be obtained by simultaneously recording behavior and brain activity. In the Go/No-go task, various ERPs components are recorded. The early components (P1, N1 and P2), which are typically present during any visual task, are followed by two later components specifically modulated by the Go/No-go condition: first a negative component (N2) and then a positive deflection (P3). The N2 component is maximal in fronto-central sites and is larger in the No-go than in the Go condition. N2 peaks around 250-300 ms, is maximal at medial frontal sites, and is considered an important marker of motor inhibitory processes (Di Russo et al., 2006; 2009). The P3 component (latency range 300-600 ms) is maximal in the centro-parietal site for Go trials and in the fronto-central sites for No-go trials (Salisbury et al., 2004; Di Russo et al., 2006; 2009) and reflects multiple processing related to the stimulus and response evaluation.

Only one study on basketball Paralympic athletes has evaluated the contributions of selected fundamental factors to performance measured by season statistics and coaches' evaluations. It showed that choice RTs, not simple RTs, contribute to performance (Wang, Chen, Limroongeungrant and Change, 2005). Thus, basketball players should have an advantage over swimmers only in the discrimination task. However, the ability to react fast to a stimulus when executing the same response (simple response task) is required in both sports (e.g. starting at the start signal). Thus, at the behavioral level sports should improve this simple reaction time skill in both disabled groups and compensate for the impairment with respect to able-bodied controls, as found by Plinta et al. (2005).

Note that electrophysiological components are particularly useful for detecting differences among groups when overt responses are unavailable, *i.e*, in the No-go condition. The ability to inhibit a programmed action is common in basketball players and is reflect mainly as an enhanced N2 component.

Material and Methods

Subjects

The study included 35 participants; 17 disabled athletes, including nine wheelchair basketball players (mean age 35.3; SD 1.9 years) and eight swimmers (mean age 33.3; SD 9.9); and 18 healthy non-athletes (mean age 34.8 years; SD 4.6). The three groups were matched for age, gender, education level, and hand preference (chi squared ns). Both basketball players and swimmers suffered from physical disability of the lower limbs (see Table 1). Most of the patients suffered SCI and amputations, which in all cases were due to accidents. Only in one case (DA #1), the presence of severe TBI followed by coma was recorded. However, this case presented no cognitive impairment. Time from onset was very long, with an average of 16.1 years (range 6-34 years). In two disabled athletes, the etiology was poliomyelitis infection in early infancy.

The athletes had at least six years of sports experience and had participated in national and international championships; some also played on the Italian Paralympics team. On average, they had 9.5 years of experience and practiced their sport 8-12 hours per week. All disabled athletes except two (one in the basketball group and one in the swimmer group) did not participate to competitive sports before having disability. Healthy participants were mostly sedentary; some took part in sports activities on a non-professional level for an average of 1.1 hours per week. All subjects provided written informed consent to participate in the experiment after the procedures (approved by the local ethics committee) had been fully explained to them.

Stimuli

The fixation point was a dot (0.3x0.3° of visual angle) in the center of a computer monitor. Four configurations composed of vertical and horizontal light grey bars subtending 4x4° were presented for 260 ms on a dark grey background. The lower edge of the stimulus was centered 1° above the fixation point to stimulate only the upper hemifield and to avoid concurrent activity in visual areas with opposite geometry (such as V1) that could lead to the reduction of some ERP components. The four configurations were displayed randomly with equal probability (p=0.25); stimulus onset asynchrony varied from 1 to 2 s.

Procedure

In separate runs, subjects performed two tasks: a discriminative reaction task (DRT) and a simple reaction task (SRT). In the DRT, two configurations were defined as targets and two as non-targets. The subjects had to press a key with their right hand as quickly as possible when a target appeared on the screen (Go stimuli; p=0.5) and refrain from responding when a non-target appeared (No-go stimuli; p=0.5). The mapping of stimulus features to Go or No-go responses was counterbalanced across subjects. In the SRT, the subjects had to respond to all four configurations. Five runs of the SRT and 10 runs of the DRT consisted of a sequence of 400 SRT, Go and No-Go trials each. The order of the tasks was counterbalanced. Only trials followed by a correct response in the 100–1000 ms window were considered (responses below 100 ms were considered stimulus anticipations. Responses above 1000 ms were rejected because of the possible overlap with the presentation of the following stimulus). We excluded the first trial of each run from further analysis to avoid orienting response contamination and provided warm-up trials. The order of presentation was randomized across subjects. The duration of each run was 2 min interleaved with a pause (total duration, about 45 min).

Analysis of RTs

To investigate the possibility that longer RTs could also be more variable for the sole reason that they are farther away from the floor, the intra-individual variability of RTs was obtained using the following Intra-Individual Coefficient of Variation (ICV): ICV=standard deviation of RT/mean of RT and was calculated for each subject on each task including all responses above 100 ms. The ICV measures performance stability controlled to some degree for speed of response (Stuss et al., 2003). To quantify the "flexibility" of motor responses *i.e.* the cost of switching from inhibition to action, the switch cost was calculated in the DRT condition as the difference between RT following a No-go trial (switch condition) and RT following a Go trial (non-switch condition).

Median RTs, ICV and omissions were analyzed using a 3X2 ANOVA including the Group (basketball players vs. swimmers vs. healthy non-athletes) and Task (SRT versus DRT) as factors. Switch costs and false alarms were analyzed using a one-way ANOVA comparing the three groups. Post-hoc comparisons were conducted using the Tukey Honest Significant

Difference (HSD) test. The significance level was set at alpha=0.05. To estimate the size of the statistical effects, the partial eta squared (η_p^2) was calculated in addition to probability values.

To evaluate the general effect of sports activity on the disabled, we compared data of the disabled athletes in our study with previous data reported by Plinta et al. (2005). The comparison was possible for the SRT, because the two tasks were very similar, but not for DRT, because the tasks were dissimilar. Moreover the comparison was possible only for the SCI subjects (the amputee and neural infection samples were too small in the present study to allow comparison). We selected 12 SCI participants from the sample of 17 disabled athletes and compared their performance data with the SCI data (N=48; group A, Table 1; Plinta et al., 2005). For both studies, we normalized the performances of SCI subjects with respect to those of healthy non-athletes using the formula: ((RT of SCI – RT of Healthy Non-athletes) / RT of Healthy Non-athletes)*100.

Electrophysiological recording and analysis

Electrophysiological recording was carried out while the participants performed the tasks. EEG was recorded using the BrainVision™ system, with 64 sensors referenced to the left mastoid. Horizontal eye movements, blinks, and vertical eye movements were recorded. The EEG was digitized at 250 Hz, amplified (bandpass of 0.01–60 Hz including a 50 Hz notch filter) and stored for off-line averaging. Prior to signal averaging, data were re-referenced to linked mastoids and artifact rejection was performed to discard contaminated epochs (13% of the trials were rejected mostly for eye blinks). ERPs were averaged in epochs starting 100 ms prior to stimulus onset and lasting for 1100 ms. To further reduce high and low frequency noise, the time-averaged ERPs were band-pass filtered from 0.05 to 25 Hz. To visualize the voltage topography of the ERP components, spline-interpolated 3D maps were constructed using the BESA 2000 software.

ERPs from the SRT and DRT runs were sorted into three categories: (1) ERPs for SRT stimuli, (2) ERPs for DRT Go stimuli and (3) ERPs for DRT No-Go stimuli. Peak amplitudes (measured with respect to the 100 ms pre-stimulus baseline) and latencies of the major ERP components were calculated for each subject in the following time windows: P1 (80–150 ms), N1 (130–200 ms), P2 (180–300 ms), N2 (200–350 ms) and P3 (250–600 ms). The components identification was also guided by their polarity and topography as previously described (Salisbury et al., 2004; Di Russo et al., 2006; 2009).

Statistical analysis

Data from the P1, N1 and P3 components were evaluated with a 3X3 ANOVA including Group (basketball players vs. swimmers vs. healthy non-athletes) and Task (SRT, Go and No-Go). For the N2, a 3X2 ANOVA was used because this component was only present in the Go and No-go conditions. As P2 was present only in the SRT condition, it was analyzed using one-way ANOVA (Table 2). To estimate the size of the statistical effects, the partial eta squared (η_p^2) was also calculated. Post-hoc comparisons were conducted using the Tukey HSD test. The overall alpha level was fixed at 0.05.

Results

Behavioral data

Simple Reaction Task (SRT)

Accuracy on the SRT was high and comparable in the three groups (Figure 1a), rejected trials were 3.4, 4.7 and 1.7% in basketball, swimmers and healthy non-athletes, respectively. Most rejections (more than 97.6%) were stimulus anticipations. Mean simple reaction times and ICV on the SRT are reported in Fig. 1b and c, respectively. Post-hoc analysis showed that healthy non-athletes were about 30 ms faster ($p<0.001$) than disabled athletes; the difference between the two groups of disabled athletes was not significant. ICV was higher in swimmers ($p <0.05$) than in the other two groups, which did not differ (see Figure 1c).

To evaluate the general effect of sports activity on SCI subjects (as illustrated in the methods section), we compared the disabled athletes' data with the data reported by Plinta et al. (2005). The slowing down of simple reaction times of SCI subjects was 14% in the sedentary group (Plinta et al., 2005) vs. 7% in the athletes (present study).

Discriminative Reaction Task (DRT)

In the DRT, the number of false alarms (Figure 1d) showed a significant group effect ($F_{2,34}=5.14$, $p<0.01$; $\eta_p^2=0.257$), indicating that swimmers made more false alarms (post-hoc: $p<0.01$) than the other two groups, which had similar results.

ANOVA on DRT reaction times showed a significant Group effect ($F_{2,34}$=5.89; $p<0.01$; η_p^2=0.365). Post-hoc analysis showed that healthy non-athletes were 57 ms (11.5%) faster ($p<0.001$) than disabled athletes' groups; the difference between the two groups of disabled athletes was not significant (see Figure 1e). Rejected trials were 1.8, 3.4 and 0.8% in basketball, swimmers and healthy non-athletes, respectively. Stimulus anticipations accounted for more than 96.2% of rejections.

The ANOVA Group effect on ICV was also significant ($F_{2,34}$=9.79; $p<0.001$; η_p^2=0.257); post-hoc analysis showed that Intra-Individual Coefficient of Variation was higher in swimmers ($p<0.05$) than in the other two groups, which did not differ (see Figure 1f).

The switch cost on DRT (Figure 1g) showed a significant group effect ($F_{2,34}$=4.18, $p<0.05$; η_p^2=0.198). Post-hoc comparisons indicated that swimmers' switch-cost was larger ($p<0.01$) than that of the other two groups, which did not differ.

Table 3 reports the individual behavioural data of all disabled athletes.

Electrophysiological data

Main ERP waveforms and voltage topographies are reported in Figures 2 and 3, respectively. Results of statistical analyses are reported in Table 2.

The earliest component (P1) peaked at approximately 115 ms at bilateral parieto-occipital sites. The P1 amplitudes did not differ between Groups or Tasks. Analysis of P1 latency showed a significant Group effect. Post-hoc analysis showed that in all conditions (SRT, Go and No-go) healthy non-athletes had a shorter ($p<0.05$) P1 latency than athletes, who did not differ (Figure 4a). The difference in latency was ca. 12 ms

At approximately 180 ms, a second component, N1, peaked at bilateral occipital sites. The N1 amplitudes did not differ between groups. However, as for P1, the N1 latency was more delayed in disabled athletes (post-hoc: $p<0.05$) than in healthy non-athletes (Figure 4b). The difference in latency was ca. 17 ms

The P2 component, which was evident only in the SRT condition, peaked at approximately 250 ms on bilateral parietal-occipital sites and was delayed (post-hoc: $p<0.05$) in disabled

athletes. The mean size of the group difference was 20 ms (Figure 4c). P2 amplitudes did not differ significantly among groups.

The N2 component peaked around 280 ms at medial central sites in the Go condition and shifted anteriorly in the No-go condition (Figures 2 and 3b). Statistical analysis shows that swimmers' N2 latency was about 45 ms (post-hoc: $p<0.05$) longer than that of the other two groups. Basketball players and healthy non-athletes did not statistically differ (Figure 5a). Also, swimmers' N2 amplitude was lower (post-hoc: $p<0.05$) than that of the other two groups, which did not differ (see Figure 5b). A significant Task effect on amplitude was present (see Table 2), indicating that the N2 amplitude was larger in No-go than in Go trials.

Finally, the P3 component peaked at about 350 ms at the medial parietal sites in the SRT condition (Figure 3b), showing similar latency and amplitude in all groups (Figure 6). In the DRT conditions, P3 latency was longer than SRT (i.e., peaking at about 450-500 ms) and, as for the N2, its distribution shifted anteriorly (i.e. at about 450-500 ms) from central to frontal sites (Figure 3b). ANOVA on P3 latency showed a significant Group x Task interaction (Table 2). Post-hoc comparisons indicated that the Go and No-go P3 latency of healthy non-athletes was earlier ($p<0.05$) than that of the disabled athletes (who did not differ). The difference between disabled athletes and healthy non-athletes was 52 ms in the Go condition and 107 ms in the No-go condition (Figure 6a). The P3 amplitude was reduced ($p<0.05$) in both groups of disabled athletes (Figure 6b). The mean size of the group difference (difference between groups) was 2.2 μV.

DISCUSSION

Results of this study confirm that lower-limb impaired subjects have longer upper-limb motor reaction times to visual stimuli than healthy non-athletes. They also extend our knowledge showing that both ERPs components related to perceptual processing and late components related to executive processing are delayed. The consistency of findings across different measurements suggests a strong internal reliability in the results. The study also shows that an open-skill sport may partially compensate for executive control impairment by fostering stability of motor responses and favoring response flexibility.

At the behavioral level, the RT difference between disabled athletes and healthy non-athletes was present in the simple reaction task (SRT) condition, in which the disabled athletes had slower response times. When we compared the SCI data of the athletes from this study with normative data on sedentary SCI patients (Plinta et al., 2005), we found that the athletes' delay (7%) was half that reported in the former study. We interpret this reduced effect as a general advantage of sports vs. a sedentary life style. In the discriminative reaction task (DRT), the RT difference between SCI athletes and healthy non-athletes was higher than in the SRT task (11.5%). We cannot compare this result with normative data, because Plinta et al.'s (2005) tasks were different (*i.e.*, they involved multiple choice not motor inhibition.).

In support of the notion that open-skill sports may improve executive control, the ICVs of basketball-disabled athletes and healthy non-athletes were comparable; by contrast, swimmers had larger inter-trial fluctuations. Moreover, on the DRT basketball disabled athletes' accuracy and switch costs were comparable to those of healthy non-athletes, whereas swimmers switch costs were larger. Thus, basketball but not swimming may compensate for inconsistency in repeated assessment of visual-motor responses (marked by ICV) and for reduced flexibility in switching from inhibition to action (measured by switch costs) associated with disability. In swimmers, difficulty in inhibiting action was also shown by their larger number of false alarms compared to the other groups; this point will be considered below.

The slowing down of early electrophysiological visual components in the disabled participants is a novel result of the present experiment. The P1, N1 and P2 components mainly represent stimulus-related activity in the occipital areas and are also sensitive to selective attention (e.g. Di Russo et al 2003, 2005; Martinez et al. 2006). The delay of these components with respect to healthy non-athletes ranged from 12 to 20 ms, which is a sizable difference; note that a similar size is reported as an effect of age in old subjects with respect to young subjects (Curran et al., 2001). The slowing down of processing and transmission across cortical areas was not associated with amplitude reduction or loss of stimulus information. Although RTs were slower in the disabled participants, accuracy was similar in the three groups, except for the swimmers' false alarms. However, false alarms do not represent a loss of information but rather a specific problem in response inhibition. Overall, the slowing down of visual processing (marked by P1, N1 and P2) contributed (by ca. 20 ms) to the marked (on average, 60 ms) RT slowing down observed in both disabled groups.

The late task-related components (N2 and P3) reflect cognitive-executive processing in parietal and frontal areas. In agreement with other reports, the N2 component was larger in the No-go than the Go trials Moreover, a clear "anteriorization" (Fallgatter et al., 1999) toward frontal leads was detected in the No-go condition with respect to the Go condition, where N2 peaked at medial central sites (Figure 3b). Overall, in the present experiment the N2 component was strongly related to action inhibition/execution processing.

Reduced N2 amplitudes have been reported in various studies (e.g. in children with attention-deficit/hyperactivity-disorder, Pliszka et al., 2000); these data were interpreted as difficulty inhibiting overbearing behavior. The reduced N2 amplitude (and longer latencies) present in disabled swimmers with respect to healthy non-athletes on the DRT might be due to executive level impairment. The reduced control of execution in swimmers is expressed at the behavioral level by a higher number of false alarms (inhibition impairment), larger ICV (instability of RTs), and higher switch costs (longer RTs when shifting from inhibition to action). By contrast, the open-skill sport enhances executive control by compensating for the disability factor: basketball athletes' N2 was comparable for amplitude and latency to that of healthy non-athletes. Furthermore, behavioral data on false alarms, ICV and switch costs matched data of healthy non-athletes.

Regarding the P3 components, in the DRT there was a large delay (60 and 100 ms for Go and No-go conditions, respectively) associated with amplitude reduction for both disabled groups. By contrast, in the SRT P3 amplitude and latency were comparable in the three groups. Thus, the "slowing down" and reduced amplitude was selective for cognitive processing related to tasks requiring visual discrimination and different responses.

At the P3 level, we did not measure differences between open- and closed-skill groups. This may be due to the multiple cortical sources of P3 involving a large number of cortical connections and associated with a large variety of cognitive tasks (e.g. Linden, 2005). Considering that the P3 peak latency was ca. 20-100 ms longer than the average reaction time, the P3 may also reflect additional processing following action execution, such as response evaluation; these processes would not be modulated in a relevant way by different sports experiences.

We can speculate that the general slowing down observed at the electrophysiological and behavioural level in both disabled groups might represent long-term consequences of undetected

(or neglected) concussions suffered during the accident, which were responsible for the loss of lower limb function. In fact, only one disabled athlete had a diagnosis of TBI, but most of them might have sustained hidden mild TBI. Some indications in the literature (ERPs study with oddball task, a paradigm sharing some aspects with the Go/No-go Task) support this view. In particular, Gosselin et al., (2006) reported amplitude reduction of N1, P2 and P3 components following concussions. In other studies, the effects of concussion (or mild brain trauma) were detected only on the late ERP components (P3), i.e., mostly on amplitude (de Beaumont, Brisson, 2007), but also on latency (Lachapelle, Bolduc-Teasdale, Ptito and Mckerral, 2008; De Beaumont, Theoret, Mongeon, Messier, et al., 2009). In fact, the effects of concussion on P3 were long lasting and could be measured even 30 years after the event (De Beaumont et al., 2009). In a previous study (Di Russo e Spinelli, 2009), we also observed a relevant delay in the P3 component of professional boxers; the latency of individual subjects was correlated with amount of boxing activity; the latter was, in turn, related to the increasing number of repeated blows to the head. Thus, at least some of the electrophysiological results reported in the present study, particularly the effects on the P3 component are compatible with the idea of a long-term effect of concussion. This explanation might also apply to previous data showing that P3 latencies are longer in amputees (Karl, Diers and Flor, 2004). In fact, upper limb amputation was the result of accidents in ca. 80% of reported cases. The long- term effects of concussion on cortical activity (on both early and late components, present data) are relevant and are often not expected in the absence of a diagnosis of brain trauma.

Not all of the observed effects were due to premorbid concussion. In fact, two disabled subjects in the present study suffered from poliomyelitis (not SCI or amputation); their data conformed to the general trend, suggesting the role of different mechanisms. Several mechanisms have been proposed in the literature. Lack of sensory afferences from the lower limbs likely has a role (Crossman, 1996). Slowing down of conduction in the cerebrospinal pathway was invoked to explain results of a transcranial magnetic stimulation study in an SCI group (Brouwer, Bugaresti and Ashby, 1992). Reduced functioning of the thalamo-cortical network was proposed to explain the EEG difference between states (open vs. closed eyes) in SCI subjects (Boord et al., 2008; Tran et al., 2004). Also, a general reduction of circulatory and respiratory capacity following the pathological event and a sedentary lifestyle may contribute in some cases (Plinta et al., 2005). However, this was not true in the present study, because all disabled participants were high-level

athletes. Indeed, the results may reflect the interaction of many mechanisms. Future studies will likely reveal the contribution of the different mechanisms responsible for the observed phenomena.

In the end, we must acknowledge a potential intrinsic limitation of the present study: we cannot exclude that disabled individuals who decide to play basketball might have better executive functioning prior to training than their peers who choose swimming. With this caution (that can be resolved only with longitudinal experiments in which disabled individuals are randomly assigned to different sports), we propose that different sports activities might have different effects in disabled individuals. Participating in an open-skill sport, such as basketball, stimulates specific executive functions. Compared to swimmers, on the behavioral task, which involved visual stimulus recognition, stimulus response mapping and motor response/inhibition, basketball players showed less variability in reaction times, fewer costs in switching from action inhibition to action execution, and higher control of action inhibition than swimmers. At the cortical level, indexed by the N2 component, action control was faster and stronger in the wheelchair basketball players. These athletes were comparable to healthy non-athletes for all behavioral and cortical aspects. Overall, the practice of open-skill sports may facilitate recovery of executive functions in physically-disabled patients.

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Figure legends

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Table 1. Demographic and clinical data of the disabled athletes. DA: disabled athlete; SCI: spinal cord injury; BKA: below knee amputation; AKA: above knee amputation; SCI and amputation were the results of accidents.

	Age	**Sex**	**Sport**	**Etiology**
DA 1	35	M	basketball	SCI
DA 2	31	M	basketball	SCI
DA 3	35	M	basketball	SCI
DA 4	40	M	basketball	SCI
DA 5	37	M	basketball	BKA
DA 6	34	M	basketball	BKA
DA 7	36	M	basketball	AKA
DA 8	36	M	basketball	poliomyelitis
DA 9	34	M	basketball	poliomyelitis
DA 10	39	M	swimming	SCI
DA 11	50	M	swimming	SCI
DA 12	38	M	swimming	SCI
DA 13	26	M	swimming	SCI
DA 14	23	F	swimming	SCI
DA 15	38	M	swimming	BKA
DA 16	28	M	swimming	BKA
DA 17	24	M	swimming	AKA

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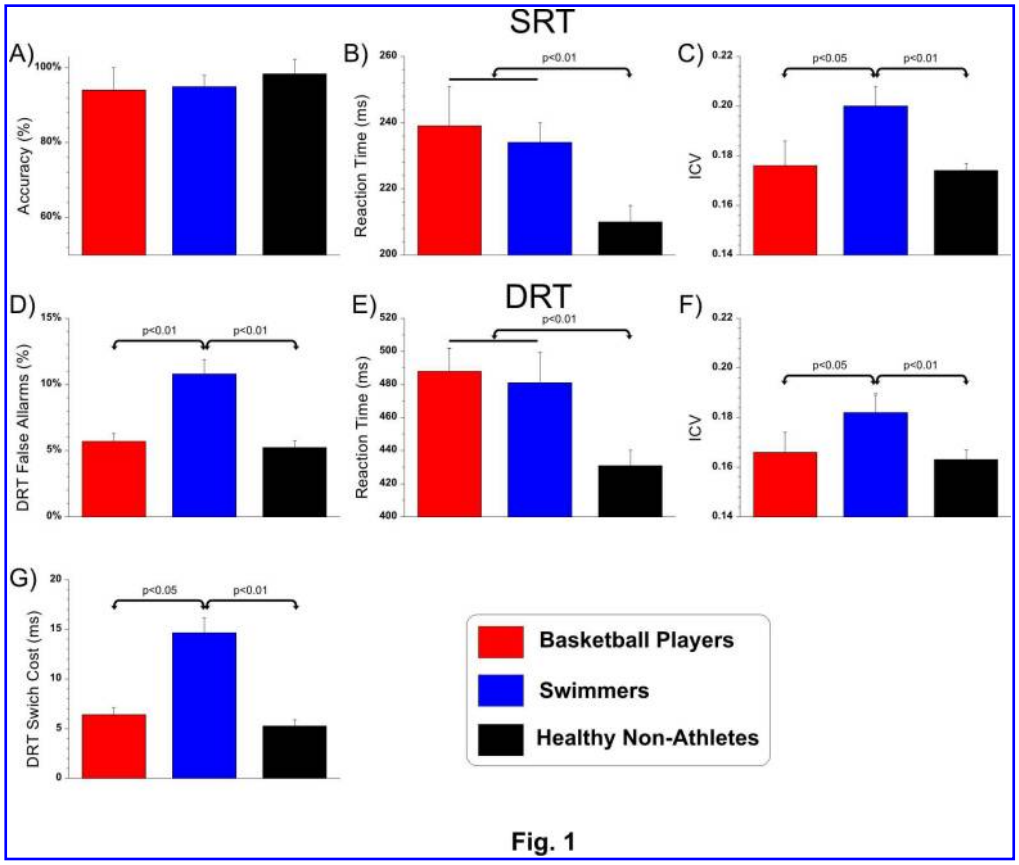
Table 2: ANOVA results for ERPs components.

	Effect DF	Error DF	F value	p value	η_p^2	F value	p value	η_p^2
ERPs Components								
P1			**Latency**			**Amplitude**		
Group	2	34	3.70	<0.05	0.149	<1	ns	0.023
Task	2	34	1.51	ns	0.035	<1	ns	0.021
Group x Task	4	68	<1	ns	0.028	<1	ns	0.026
N1			**Latency**			**Amplitude**		
Group	2	34	6.01	<0.01	0.261	1.02	ns	0.095
Task	2	34	<1	ns	0.025	4.75	<0.05	0.135
Group x Task	4	68	<1	ns	0.049	1.75	ns	0.106
P2			**Latency**			**Amplitude**		
Group	2	34	4.22	<0.05	0.156	1.63	ns	0.068
N2			**Latency**			**Amplitude**		
Group	2	34	15.22	<0.01	0.420	3.23	<0.05	0.133
Task	1	34	1.81	ns	0.041	10.22	<0.01	0.196
Group x Task	2	34	<1	ns	0.012	2.81	ns	0.099
P3			**Latency**			**Amplitude**		
Group	2	34	4.44	<0.05	0.175	4.17	<0.05	0.147
Task	1	34	123.89	<0.01	0.746	11.54	<0.01	0.456
Group x Task	4	68	3.58	<0.05	0.110	3.45	<0.05	0.105

Table 3. Individual data of the disabled athletes in simple (SRT) and discriminative (DRT) reaction task. RT: Median Reaction Time. ICV: Intra-individual coefficient of variation of the reaction time. Accuracy and false Alarms are expressed as percentage. For ICV and Switch cost computations, see methods. Disable athletes' numbers as in Table 1.

	SRT			DRT				
	RT (ms)	**ICV**	**Accuracy**	**RT (ms)**	**ICV**	**Accuracy**	**False Alarms**	**Switch Cost (ms)**
DA1	238	0.283	99.5	517	0.143	100.0	4.8	0.9
DA2	229	0.191	96.5	514	0.175	99.5	5.3	15.6
DA3	242	0.225	97.3	513	0.162	94.8	3.5	8.4
DA4	215	0.191	90.8	478	0.198	93.5	10.5	9.8
DA5	245	0.173	99.3	411	0.164	100.0	4.0	16.9
DA6	242	0.182	97.5	509	0.179	99.0	7.5	6.6
DA7	262	0.185	98.3	550	0.184	97.8	4.5	2.1
DA8	222	0.174	92.3	470	0.169	100.0	10.0	6.0
DA9	260	0.283	97.8	446	0.122	99.3	1.3	8.4
DA10	212	0.191	93.8	450	0.221	97.8	20.1	14.1
DA11	235	0.225	93.5	538	0.172	93.8	4.7	4.3
DA12	293	0.191	98.8	554	0.140	97.3	11.5	24.1
DA13	214	0.173	95.8	445	0.184	93.3	7.2	25.5
DA14	219	0.185	94.8	439	0.165	97.5	5.0	29.9
DA15	208	0.182	97.8	447	0.198	99.0	17.7	0.4
DA16	265	0.283	90.8	452	0.203	98.0	17.5	9.8
DA17	227	0.174	97.3	525	0.171	96.5	3.2	9.2



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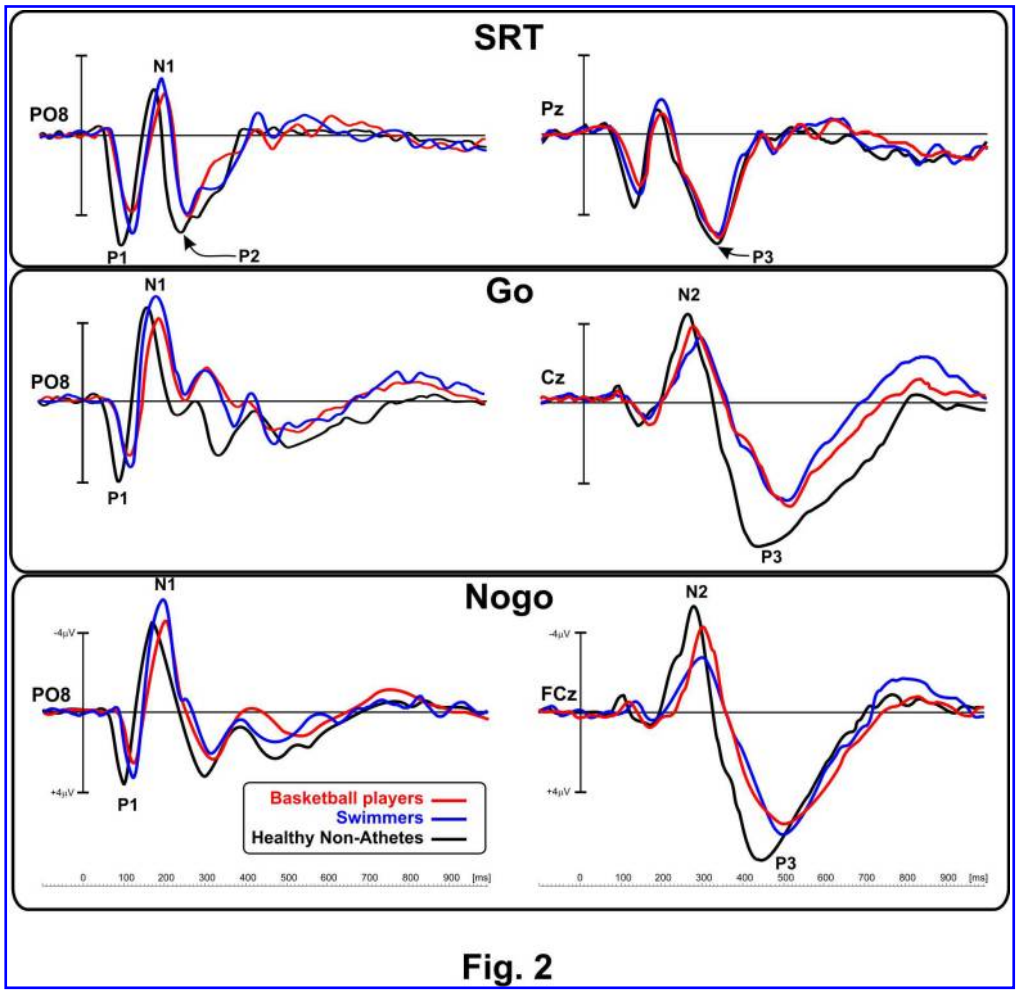

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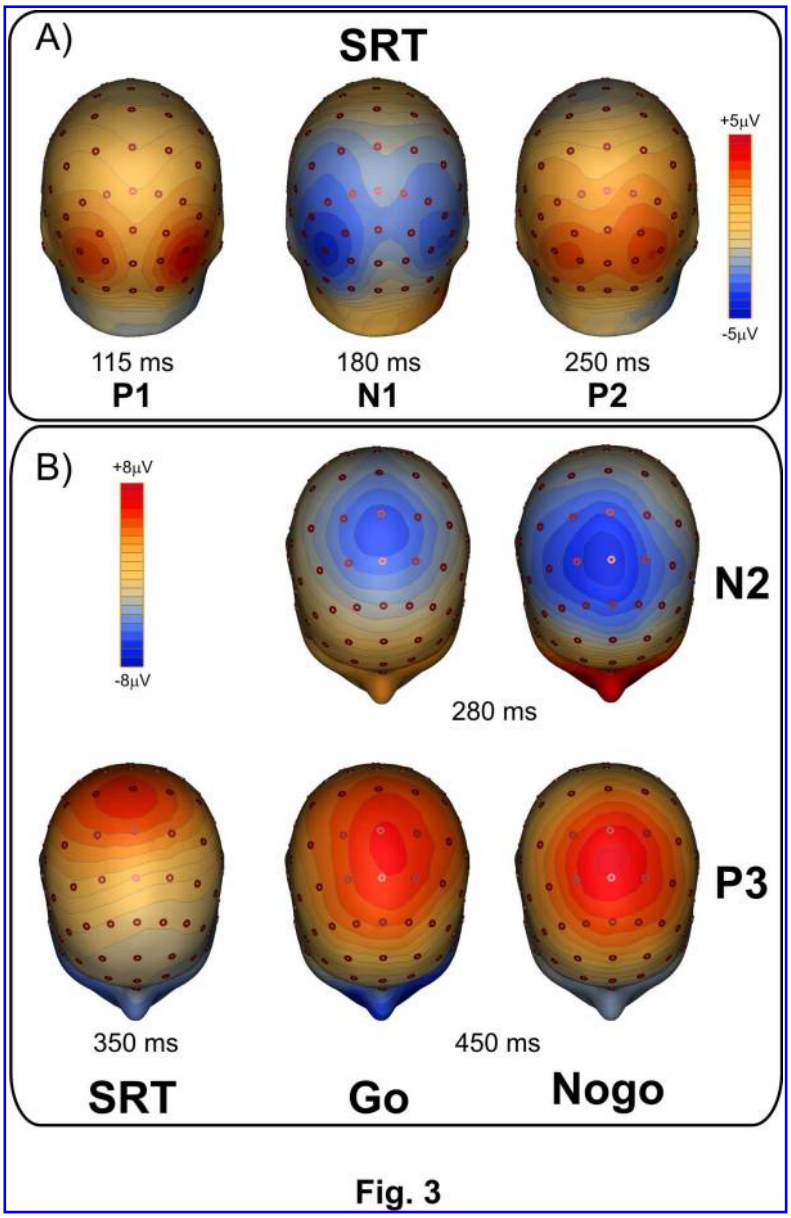
160x156mm (300 x 300 DPI)



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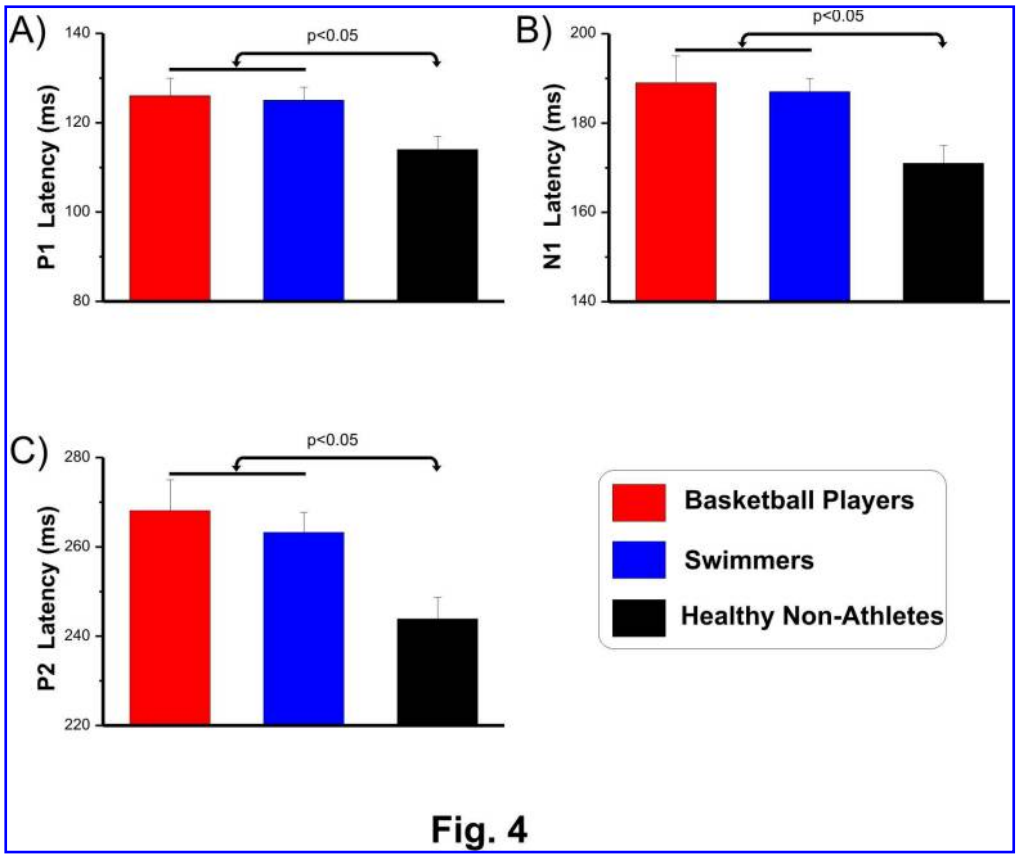
131x203mm (300 x 300 DPI)



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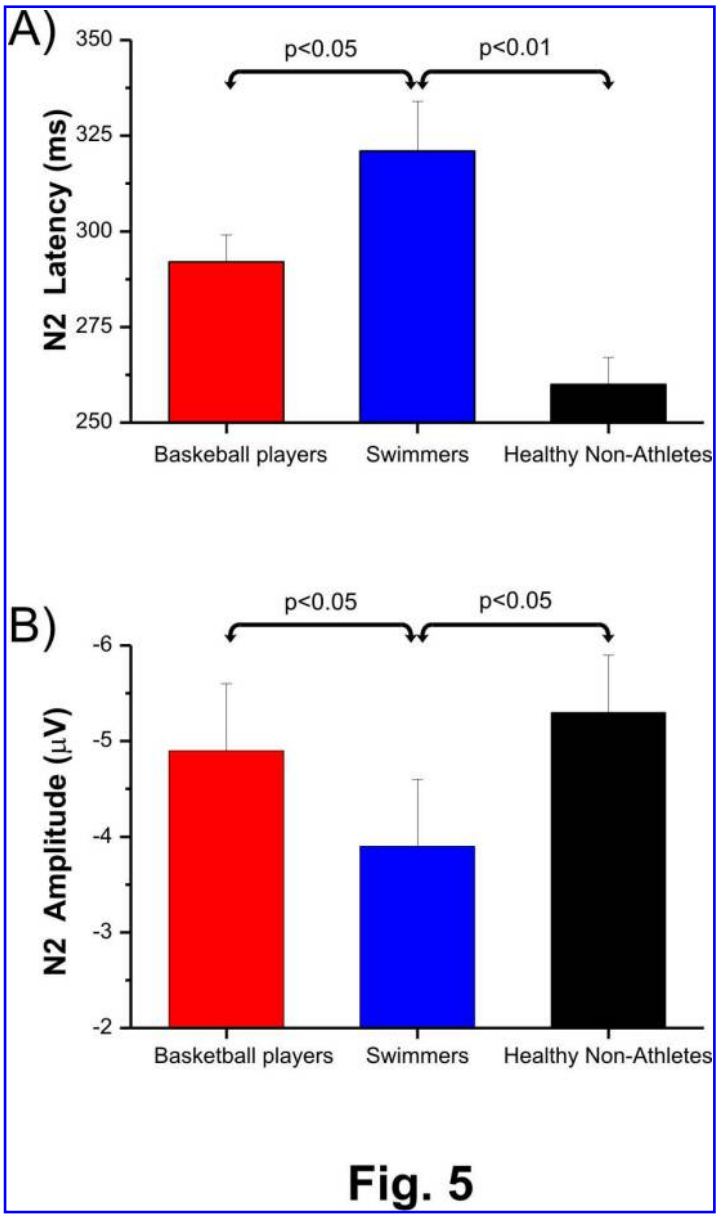
150x126mm (300 x 300 DPI)



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81x139mm (300 x 300 DPI)

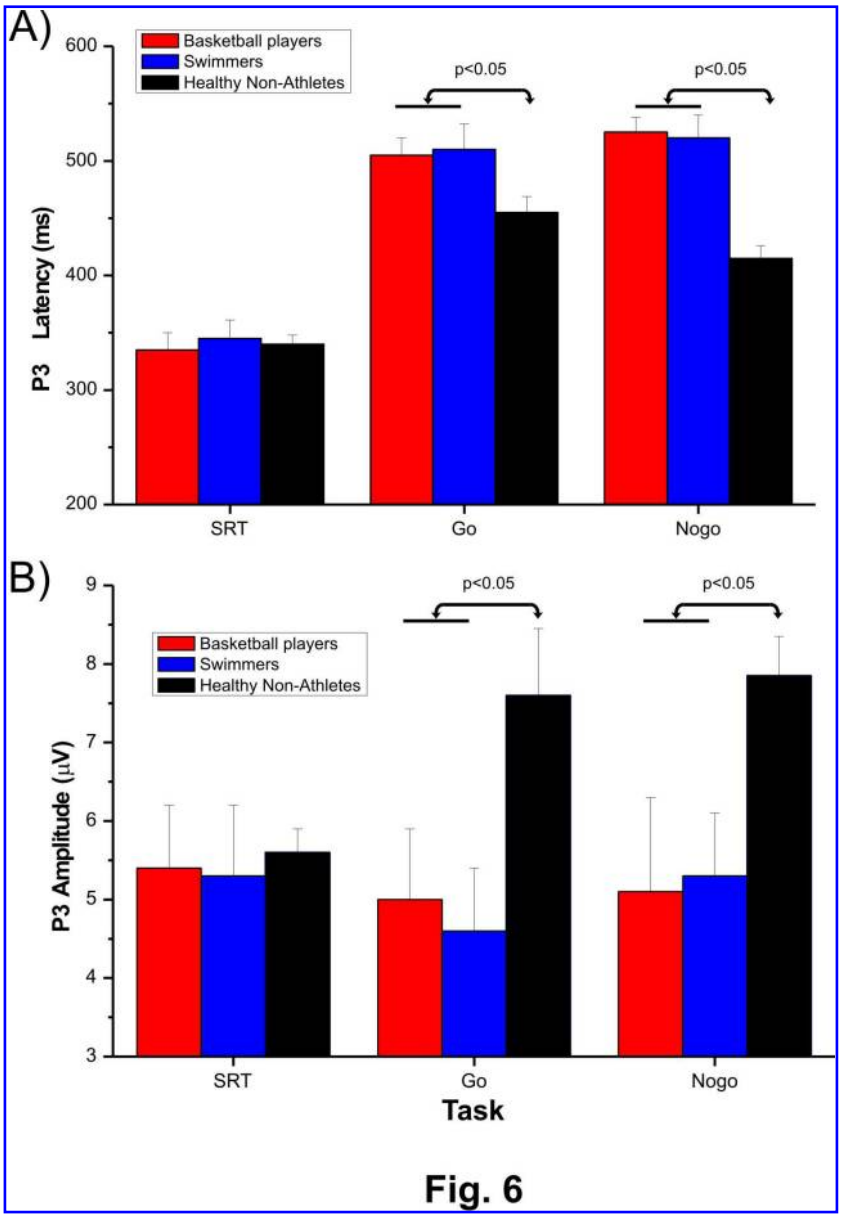

Figure 6. Means and standard deviations of the three groups in the late P3 component in SRT left) and DRT middle and right graphs). A) P3 latency; B) P3 amplitude. A separate ANOVA confirmed the absence of significant Group differences in the SRT condition.
122x177mm (300 x 300 DPI)