Sport is not always healthy: Executive brain dysfunction in professional boxers

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Abstract
We measured ERPs of professional boxers in a Go/No-Go task, comparing them to fencers and non-athletes. Results showed that fencing improved attention and motor response control, but boxing did not. More strikingly, in boxers, as in brain trauma patients, the P3 component was delayed and reduced. The P3 delay of boxers was correlated with the amount of performed sport exercise. Furthermore, in terms of behavior, boxers showed increased intra-individual variability and switch cost. Results were consistent with the hypothesis of specific impairment at the level of response inhibition processing. We suggest that this impairment is derived from the cumulative effect of blows to the head. The changes found in boxers suggest that ERPs and reaction times may be a tool for early detection of specific brain dysfunction.

Descriptors: Brain trauma, ERPs, Executive control, Sport, Boxing

Practicing sport is one of the best activities for promoting mental and physical health; however, it can carry risks. The present study investigated athletes practicing the traditional discipline of boxing.

It is well known that in severe cases, brain injury from repetitive head blows in boxers may result in dementia pugilistica and parkinsonism. However, it is also relevant to evaluate cases that are much less severe and more frequent, such as cumulative effects of non-severe head injuries in young and healthy boxers. The evidence of traumatic brain injury (TBI) in the boxer population is still controversial (Loosemore, Knowles, & Whyte, 2007). Mild effects of concussion are difficult to detect with computed tomography (CT) or conventional magnetic resonance imaging (MRI); for instance, Haenel and colleagues (2008) reported a statistically non-significant prevalence of cerebral micro-hemorrhages in boxers. Only the use of a technique more sensitive to micro-structural changes (diffusion tensor imaging [Chapell et al., 2006]) revealed diffuse brain damage in professional boxers. This brain damage involved both white and grey matter, and was more evident in professional boxers than in amateur boxers due to greater exposure to injury by professionals.

Electrophysiology may prove to be a more sensitive technique than conventional MRI for showing effects of sports concussions. In symptomatic and asymptomatic hockey and football players, concussions seem to produce deficits both at the early and late stages of neural processing as indicated by N1, P2, and P3 amplitude reduction in an auditory oddball task (Gosselin, Theriault, Leclerc, Montplasir, & Lasonde, 2006). Modifications limited to the P3 component were described by other authors. In a visual oddball task, the P3 amplitude varied inversely with the severity of post-concussion symptoms in asymptomatic concussed athletes (Lavoie, Dupuis, Johnston, Leclerc, & Lassonde, 2004). P3 suppression was long-lasting: three years after the event, multi-concussed athletes showed P3 amplitude suppression while the N2pc component was intact (de Beaumont, Brisson, Lassonde, & Jolicoeur, 2007). Even 30 years after concussion, effects on amplitude (and latency) of P3a and on latency of P3b were detected in an auditory oddball task (De Beaumont et al., 2009). To date, electrophysiological studies on boxers have been few and inconclusive. Thomasse, Jul Jensen, de Fine Olivarius, Braemer & Christensen (1979) examined the electroencephalograms (EEGs) of a large number of former champion amateur boxers with those of a control group consisting of former football players, and no difference was found. McLatchie et al. (1987) found that 8 of 20 amateur boxers had abnormal EEGs as determined by slow activity or a dominant 7 Hz rhythm. In an event-related potential (ERP) study of attention and orienting reaction in boxers before and after a fight, Breton, Pincemaille, Tarriere, & Renault (1991) found no abnormalities of attention or detection processes. However, a slight deficit was observed in the orienting reaction toward stimuli delivered to the right ear, an effect that was related to a greater number of blows delivered on the left side of the head.

In the present study, we investigated the brain activity and reaction time (RT) of boxers using a Go/No-Go task. We selected this task for two reasons. First, it seems appropriate
to highlight possible functional defects because it resembles the Zimmermann test, which is widely used in neuropsychological assessment (e.g., Zimmermann & Fimm, 2002). Deficits in the Zimmermann test have been reported mainly in patients with frontal lesions and are interpreted as impairment of voluntarily controlled actions (e.g., O’Keeffe, Dockree, Moloney, Carton, & Robertson, 2007). Second, the task mimics cognitive and executive functions (fast stimulus discrimination, response selection, and motor reaction or inhibition) that are particularly relevant in combat sports such as boxing. For this reason, we adopted the Go/No-Go task in a previous study on professional fencers and found that fencing produced relevant cortical effects: a) the attentional modulation of visual processing in the occipital lobes was enhanced; b) activity associated with the stimulus discrimination stage was faster than in controls; and c) activity associated with the response selection stage, particularly with the motor inhibition process, was stronger than in controls. Overall, this system provided a measure of the positive effects of sport practice on cortical mechanisms responsible for processing from the perceptual to executive stages (Di Russo, Taddei, Aprile, & Spinelli, 2006).

Except for the physical contact involved, boxing is a combat sport similar in many respects to fencing. Thus, in principle, we may observe electrophysiological patterns in boxers similar to those of fencers. Alternatively, we may expect that, in boxers, repetitive head blows might affect electrophysiological activity and thus result in dysfunctions with respect to normal activity. The effect of head blows on cortical activity might be ubiquitous, as indexed by a general electrophysiological suppression or delay. In this case, we should expect a reduction in the amplitudes of all components (such as observed in other sports by Gosselin et al., 2006). Alternatively, the effect might be specifically linked to P3, as suggested by other studies (Lavoie et al., 2004; de Beaumont et al., 2007) and may involve latency changes (de Beaumont et al., 2009).

We simultaneously measured ERPs and RTs. To evaluate possible subtle impairments at the behavioral level, we studied short-term fluctuations in performance by calculating the intra-individual variability of RTs (Stuss, Murphy, Binns, & Alexander, 2003). Increased intra-individual variability can be an important functional marker. Focal lesions of the frontal lobes impair stability of behavior and lead to increased intra-individual variability of RTs (Stuss et al., 2003). Increased variability was also observed in cases of non-focal TBI at all levels of severity (reviewed in Stuss et al., 2003). In patients, increased intra-individual variability is often, but not always, associated with lengthening of RTs (Stuss et al., 2003); thus, we may expect that intra-individual variability in boxers would be enlarged, even if the mean RTs of the group are not different from the mean RTs of control groups. Also, we considered the cost for switching from one action to another. In the discriminative task, a “Go” response could follow an identical “Go” response or a “No-Go” response. In the first case, the proper task-set remains activated in place from the previous trial, whereas in task switch trials, the task-set must be reconfigured. Thus, we can evaluate the switch cost with respect to repetition of the same action. Increased switch cost, often associated with more errors in task switch trials, is typical of patients with frontal damage (Aron, Monsell, Sahakian, & Robbins, 2004). Boxers may show increased switch cost with respect to subjects from non-concussed groups.

Material and Methods

Subjects
The study consisted of 36 subjects; the sample included twelve boxers (mean age 28.1 years; SD 5.5; 4 females), twelve fencers (mean age 26.3 years; SD 6.5; 5 females) and twelve non-athlete students (mean age 25.8 years; SD 3.8; 5 females). Nine boxers, ten fencers and ten students had right-hand dominance. The three groups were matched for age, gender, education level, and manual preference (chi square, ns). No neurological signs were reported in any participants. The athletes had at least 6 years of sport experience and had participated in national and international championships. On average, the boxers and fencers had 13.3 and 10.5 years of experience, respectively, and practiced for 8.8 and 8.2 h per week, respectively. Students practiced various sports on a non-professional level for an average of 2.3 h per week, but none had experience in fencing or boxing. The hours of practice were not different between the two groups of athletes (chi square, ns). Boxers had sustained at least one knock-out (mean 3.1). 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 cross (0.3 × 0.3° of visual angle) in the centre of a computer monitor. Four squared configurations made of vertical and horizontal bars subtending 4 × 4° (see Figure 1a) were presented for 250 ms on a dark grey background. The lower edge of the stimulus was centred 1° above the fixation point.

Figure 1. a) The four stimulus configurations used in the experiment. b) Reaction time in the three groups and in the two conditions studied. Behavioral data also included measurements of accuracy. No errors were observed in the SRT; in DRT, false positives amounted to 11.4% (Boxers), 12.8% (Fencers), and 9.5% (Non-Athletes); misses amounted to 0.8% (Boxers), 1.1% (Fencers), and 1.3% (Non-Athletes).
Executive brain dysfunction in boxers

Table 1: ANOVA Results of ERPs Components, Difference Waves and Dipole Activity

<table>
<thead>
<tr>
<th>ERP Components</th>
<th>Effect DF</th>
<th>Error DF</th>
<th>F value</th>
<th>p value</th>
<th>$\eta^2_p$</th>
<th>F value</th>
<th>p value</th>
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<tr>
<td>P1</td>
<td>Group</td>
<td>2</td>
<td>32</td>
<td>&lt;1</td>
<td>ns</td>
<td>1.02</td>
<td>ns</td>
<td>.012</td>
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<td></td>
<td>Task</td>
<td>2</td>
<td>66</td>
<td>&lt;1</td>
<td>ns</td>
<td>.005</td>
<td>1.67</td>
<td>ns</td>
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<tr>
<td></td>
<td>Group × Task</td>
<td>4</td>
<td>66</td>
<td>&lt;1</td>
<td>ns</td>
<td>.03</td>
<td>1.45</td>
<td>ns</td>
</tr>
<tr>
<td>N1</td>
<td>Group</td>
<td>2</td>
<td>32</td>
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<td>ns</td>
<td>.019</td>
<td>6.38</td>
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<td>ns</td>
<td>.007</td>
<td>4.43</td>
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<td>4</td>
<td>66</td>
<td>&lt;1</td>
<td>ns</td>
<td>.008</td>
<td>4.65</td>
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<td>32</td>
<td>&lt;1</td>
<td>ns</td>
<td>.011</td>
<td>&lt;1</td>
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<td></td>
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<td>&lt;1</td>
<td>ns</td>
<td>.014</td>
<td>3.25</td>
<td>&lt;0.05</td>
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<td>ns</td>
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<tr>
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<td>Group</td>
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<td>&lt;1</td>
<td>ns</td>
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<td>4.54</td>
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<tr>
<td>P3</td>
<td>Group</td>
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<td></td>
<td>Task</td>
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<td>32</td>
<td>3.31</td>
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<td>.352</td>
<td>3.07</td>
<td>&lt;0.05</td>
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<td>&lt;1</td>
<td>ns</td>
<td>.024</td>
<td>4.32</td>
<td>&lt;0.05</td>
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<tr>
<td>Go minus NoGo ERPs</td>
<td>Group</td>
<td>2</td>
<td>32</td>
<td>&lt;1</td>
<td>ns</td>
<td>.026</td>
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<td>450 ms</td>
<td>Group</td>
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<td>32</td>
<td>&lt;1</td>
<td>ns</td>
<td>.026</td>
<td>3.25</td>
<td>&lt;0.05</td>
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<td>ERP Source Activity</td>
<td>AGC onset</td>
<td>2</td>
<td>32</td>
<td>6.25</td>
<td>&lt;0.01</td>
<td>.501</td>
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<td></td>
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<tr>
<td>N1</td>
<td>DSPC onset</td>
<td>2</td>
<td>32</td>
<td>7.43</td>
<td>&lt;0.01</td>
<td>.543</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>AGC peak</td>
<td>2</td>
<td>32</td>
<td>8.21</td>
<td>&lt;0.01</td>
<td>.598</td>
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<td>&lt;0.05</td>
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<td></td>
<td>DSPC peak</td>
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<td>32</td>
<td>9.14</td>
<td>&lt;0.01</td>
<td>.602</td>
<td>2.12</td>
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</table>

Procedure

In separate runs, subjects performed two tasks: a discriminative reaction task (DRT) and a simple reaction task (SRT). In DRT, two configurations were defined as targets and two as non-targets. The subjects had to press a button with their right hand as quickly as possible when a target appeared on the screen (Go stimuli; $p = 0.5$), and they withheld the response when a non-target appeared (No-Go stimuli; $p = 0.5$). The mapping of stimulus features to Go or No-Go responses were counterbalanced across subjects. In the SRT, subjects had to respond to any of the four configurations. Four runs of the SRT and eight 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. The first trial of each run was excluded from further analysis to avoid orienting response contamination; warm-up trials were provided. The order of presentation was randomized across subjects. The duration of each run was 2 min followed by a pause (total duration about 30 min).

Analysis of RTs

RTs for correct trials were analyzed in the 100–1000 ms window. 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 within each task (from Stuss et al., 2003). The switch cost was calculated as the difference between RT following a No-Go trial and RT following a Go trial.

Median RTs and ICV were analyzed using a 3 × 2 ANOVA including the groups (boxers versus fencers versus non-athletes) and task (SRT versus DRT) as factors. The switch cost was analyzed using a one-way ANOVA comparing the three groups. Post-hoc comparisons were conducted using the Tukey HSD (honest significant difference) test. The overall alpha level was fixed at 0.05.

Electrophysiological Recording And Analysis

EEG was recorded using the BrainVision system (Brain Products GmbH, Munich, Germany) 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 (band-pass of 0.01–60 Hz including a 50 Hz notch filter) and stored for off-line averaging. Computerized artefact rejection was performed prior to signal averaging in order to discard epochs contaminated by artefacts (13% of the trials were rejected). 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 three-dimensional 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 No-Go stimuli, and (3) ERPs for Go stimuli.

Peak amplitudes (measured with respect to the 100 ms prestimulus 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).

**Statistical Analysis**

Data from P1 and N1 were evaluated with a $3 \times 3$ ANOVA that included the groups (boxers versus fencers versus non-athletes) and task (SRT, Go, and No-Go). For N2 and P3, a $3 \times 2$ ANOVA was used, as these components were present only in the Go and No-Go conditions. For P2, which was present only in the SRT condition, one-way ANOVAs were performed. To estimate the size of the statistical effects, the partial eta squared ($\eta_p^2$) was calculated in addition to probability values (Table 1). Given that No-Go ERPs are usually larger than Go ERPs (especially for N2 and P3 components), we isolated ERP components associated with response inhibition (e.g., Ritter, Simson, Vaughan, & Macht, 1982; Bekker, Kenemans, & Verbaten, 2005) by subtracting Go from No-Go ERPs (No-Go minus Go). One-way ANOVAs were performed on the difference components and on the estimated intra-cranial source activity (see below) onset and peak latency. Considering that normal aging affects ERP components (in particular P3) by reducing amplitudes and increasing latency (Polich, 1996; Rossini, Rossi, Babiloni, & Polich, 2007), we included the subject’s age as a covariate in all ANOVA designs. The sensor sites included in the analysis were selected according to the component peak amplitude. Greenhouse-Geisser correction and Tukey HSD post-hoc were applied. For statistical correlations between behavioral and electrophysiological data, the $r$ Pearson coefficient was used. Significance was accepted for $p < 0.05$.

**ERP Source Analysis**

Estimation of the intracranial sources of differential ERP components was carried out using Brain Electrical Source Analysis (BESA 2000 version 5.14) in order to estimate the cerebral areas involved in response inhibition and test possible differences in the temporal evolution of these areas across the three groups of subjects. The BESA algorithm estimates location, orientation, and time course of multiple equivalent dipolar sources by calculating scalp distribution, which is obtained for a given dipole model (forward solution). This distribution is then compared to that of the actual ERPs. Interactive changes in location and orientation in the dipole sources lead to minimization of residual variance between the model and the observed spatio-temporal ERP distribution. Electrode position was digitized and averaged across subjects. The three-dimensional coordinates of each dipole in the BESA model were determined with respect to the Talairach axes and scaled according to brain size.

Based on the assumption that ERP sources did not differ in location between the three groups, a single general model was obtained from the grand average of all 36 subjects and then applied to the three groups by fixing the dipole location obtained from the general model and then fitting only the dipole orientation. Given the wide medial or bilateral scalp topography of differential ERP components, bilateral pairs of sources were used. To limit the number of parameters to be estimated, symmetry constraints with respect to location and orientation were applied for each bilateral dipole pair. The possibility of interacting dipoles was reduced by selecting solutions with relatively low dipole moments with the aid of an “energy” constraint (weighted 20% in the compound cost function, as opposed to 80% for the residual variance). The optimal set of parameters was found in an iterative manner by searching for a minimum in the compound cost function. Dipole pairs were fit sequentially. Latency ranges for fitting were chosen (see below) to minimize overlap among successive, topographically distinctive components. Dipoles accounting for earlier portions of the waveform were left in place as additional dipoles were added. The reported dipole fits were found to remain consistent for different starting positions. The dipole fitting strategy was as follows: two bilateral mirrored symmetric dipole pairs were sequentially fit to the component at 280 and 450 ms, respectively, accounting for more than 97% of the variance in scalp voltage topography over the 200–550 ms time range, indicating high likelihood of the model (for more detail, see Di Russo, Pitzalis, Aprile, & Spinelli, 2005). Statistical comparisons between onset and peak latency of dipole activity were employed by applying the group model individually to every subject.

![Figure 2](image)

**Results**

**Behavioral Data**

Task accuracy for the three groups was similar (approximately 90%). There was no significant difference in the SRT RT. The
DRT RT was similar for the three groups, with the only significant difference being that fencers were faster than non-athletes ($F_{1,32} = 5.7, p < 0.01$; post-hoc $p < 0.01$) as compared to the other groups (which did not differ). There were no significant ICV differences on the SRT.

The switch cost on DRT (Figure 2b) showed a significant group effect ($F_{1,32} = 8.6, p < 0.01$); boxers' switch cost was larger (post-hoc $p < 0.01$) than that in the other two groups. Fencers had a lower switch cost than non-athletes (post-hoc $p < 0.05$).

**Figure 3.** a) Grand-average ERPs at relevant sensors for the three groups (represented by different colours) in the three conditions (SRT, DRT-Go, DRT-No-Go). SRT: no difference between groups. DRT-Go and No-Go, bottom traces: note the larger amplitude of the N1 component at the parieto-occipital sensors in fencers due to attentional modulation. DRT-No-Go: note the larger amplitude of the N2 component in fencers at the frontal electrodes (top) and the longer latency of P3 in boxers at the Cz sensor. Boxers’ P3 also had longer latency in the Go trials. b) Voltage topographies of the major ERP component in the DRT condition. Data between subjects were averaged because of very similar topographies. Note the P3 “anteriorization” in the No-Go condition.

The mean ICV for each group on each task is presented in Figure 2a. ICV was significantly higher on the DRT for boxers ($F_{1,32} = 5.7, p < 0.01$; post-hoc $p < 0.01$) as compared to the other groups (which did not differ). There were no significant ICV differences on the SRT.
Electrophysiological Data

ERP waveforms and voltage topographies are reported in Figure 3a and Figure 3b, respectively. Results of statistical analysis are reported in Table 1, and the more interesting comparisons were plotted in Figure 4.

The earliest component (P1) peaked at approximately 100 ms at bilateral parietal-occipital sites. P1 amplitudes and latencies did not differ between groups or conditions. The Group × Task interaction was not significant. Similarly, P2 (evident only in the SRT condition) peaked at approximately 220 ms on bilateral parietal-occipital sites and did not differ between groups.

In contrast, interesting differences were observed in other ERP components. The Go and No-Go N1, peaking at approximately 180 ms at bilateral occipital sites, were larger in fencers than in boxers and non-athletes (Figure 4a); post-hoc comparison of the significant factor interaction indicated that fencers (but not boxers) had stronger (p<0.05) attentional modulation of visual processing (as indexed by N1, see Vogel & Luck, 2000).

The No-Go N2, which peaked around 280 ms at medial frontal sites, was larger in fencers than in boxers and non-athletes (Figure 4b). Post-hoc comparison of the significant factor interaction indicated that fencers had larger amplitude (p<0.05), indicating stronger motor inhibition processing (e.g., Bekker et al., 2005). The No-Go N2 amplitude was larger (p<0.05) than Go N2 in all groups. Other comparisons were not significant.

In addition, the P3 component showed a significant Group × Task interaction for both amplitudes and latencies (Table 1). Post-hoc comparisons indicated that the Go P3 amplitude (peaking at the medial parietal sites) was reduced (p<0.05) in boxers, whereas the No-Go P3 amplitude (peaking at medial frontal sites) was enlarged in fencers (Figure 4c). More strikingly, the P3 component was delayed in boxers (p<0.05 and p<0.01 for Go and No-Go conditions, respectively) as compared to the other groups (Figure 4d), indicating a slowing of mental processes during the DRT. Other comparisons were not significant.

In terms of the scalp distribution of these ERP components, no change in topography was observed except for P3, which became more anterior in the No-Go condition.

The individual subject analysis is reported to show the reliability of ERP data. The No-Go N1 amplitude was consistently larger in all fencers, No-Go N2 was larger in 67% of fencers (Figure 5a), and P3 was systematically delayed in all boxers (Figure 5b).

The total amount of boxing activity (approximate number of hours spent in this activity throughout life) showed a significant positive correlation with the P3 latency during the No-Go condition, but not during the Go condition (Figure 5c). No other tested correlations was significant.

Subtraction waves (No-Go minus Go ERPs) were used to isolate the stronger No-Go N2 and the typical anteriorization of the P3 component (Fallgatter & Strik, 1999). This comparison elicited two major components (Figures 6a, b) peaking around 280 and 450 ms, just about the latencies of N2 and P3. The first component showed a negative focus at medial frontal sites, the second showed a bipolar distribution with a positive peak at the same sites and a negative focus at medial parieto-occipital sites. Statistical analysis confirmed slower processing in boxers; resultant activity, which is associated with response inhibition (e.g., Ritter et al., 1982; Bekker et al., 2005), was clearly delayed. Neural mechanisms that control inhibition were initiated in boxers at 230 ms at medial frontal sites and peaked at 325 ms and 450 ms (Figures 6a, b). The corresponding timing was earlier (p<0.05) in fencers and non-athletes, beginning at 200 ms and peaking at 280 and 450 ms; these values did not differ from each other (see Table 1 for detailed ANOVA results).

Source analysis was applied to the subtraction waves of the three groups; this brain activity was bilaterally localized in two separate structures (Figure 6c) within the anterior cingulate gyrus (ACG) in the prefrontal cortex and in the dorsal superior parietal cortex (DSPC). The residual variances of the source models (indicating the likelihood of the model) were 2.6, 3.1, and 2.8% for boxers, fencers, and non-athletes, respectively. The waveforms
shown in Figure 6c represent the source time course (dipole moment) in the three groups and show that the source in the ACG starts its activity around 200 ms and peaks around 300 ms. Statistical analysis (Table 1) showed that the onset and the peak of this activity was delayed in boxers, starting 30 ms and peaking 50 ms later ($p < 0.01$), than in fencers and non-athletes (which did not differ). The source in the DSPC started its activity around 300 ms and peaked around 450 ms. Statistical analysis (Table 1) showed that also the onset and the peak of this activity were delayed in boxers ($p < 0.01$) when compared to fencers and non-athletes (which did not differ). No statistical difference was found for the peak intensity of the DSPC source.

**Discussion**

The electrophysiological and behavioral patterns of professional boxers and fencers were remarkably different. Long-term sport training in fencers promoted faster and more efficient processing (Di Russo et al., 2006; present study) and fencing improved visual attention (as determined by the enhancement of the N1 component) and the inhibition of motor responses (as determined by the N2 component). At the behavioral level, fencers had low switch costs. On the other hand, boxers showed several drawbacks. At the electrophysiological level, boxers showed increased P3 latency and reduced amplitude; at the behavioral level, they showed larger inter-trial fluctuations indicating inconsistency over repeated assessments, and greater switch costs in action selection when performing a discriminative response task.

Despite the comparable amount of sport training (both groups were professional) and the similar age of the athletes, the results suggest a specific deterioration of executive processing in boxers. We interpret these results as a consequence of repetitive head blows associated with professional boxing.

Electrophysiological changes recorded in boxers were not ubiquitous, but selective. Consistent with observations in athletes from other sport disciplines exposed to concussion (Lavoie et al., 2004; de Beaumont et al., 2007; de Beaumont et al., 2009), the effect was specifically linked to the P3 component in terms of amplitude reduction and latency delay. The positive correlation between the overall quantity of time spent boxing and the length...
of No-Go P3 latency support the view that the electrophysiological delay is a consequence of the number of sustained head blows, which grows with increasing practice. This interpretation is also supported by the data of Chapell et al., 2006, which revealed diffuse brain damage in professional boxers, and by convergent evidence from de Beaumont et al. (2009) detecting a latency effect on P3 as long as 30 years after concussion in hockey and football players. Finally, similar (and more exaggerated and more diffuse across components) effects on ERP and behavior have been reported in patients with TBI (Roche et al., 2004; Stuss et al., 2003). As in these patients, we find in boxers a significant impairment in inter-subject variability and switch costs. ERPs in response to the Go/No-Go task appear to be a sensitive tool, particularly when associated with behavioral measures (accuracy and RTs measured in the same task, simultaneously with electrophysiological recording), for early diagnosis of mild brain dysfunction.

An alternative interpretation is that the results were derived from specific strategies employed by boxers. Boxers may have learned to “non-inhibit” their actions, because it is not possible
to correct a very fast action (less than 80 ms) once it has started. Anyway, it is hard to believe that repeated brain concussions do not have a major role in the observed dysfunctions. Imaging methods have been developed to provide a more sensitive assessment of structural and functional abnormalities following mild TBI (e.g., Giugni, Sabatini, Hagberg, Formisano, & Castrioti-Scanderbeg, 2005; Mendez, Hurley, Lassonde, Liying, & Taber, 2005; Belanger, Vanderploeg, Curtiss, & Warden, 2007). Future experiments associating ERP data and sensitive functional and structural brain imaging may support the present conclusion, and we are planning to apply them to athletes engaged in combat sports.

In gaining a better understanding of the link between P3 modification and associated processing, we believe that subtraction waves and the results of the localization study presented here can be useful. P3 is a complex component that reflects multiple processes, including stimulus-related categorization (e.g., Dien, Spencer, Donchin, 2004) as well as response-related processes (Verleger, Jaskowsky, & Wascher, 2006) such as inhibition (e.g., Gajewski, Stoerig, & Falkenstein, 2008). Subtracting the Go response from the No-Go response, we obtained a wave expressing the maximum differences between execution and inhibition processing that was more prominent in frontal areas (Figure 5b). This subtraction wave appears to be dominated by inhibition processing, as suggested by several authors (e.g., Ritter et al., 1982; Dias, Foxe, & Javitt, 2003; Bekker et al., 2005). Considering that categorization is present in both Go and No-Go trials, differential activity in the P3 time window (300–500 ms) might reflect inhibition-related processing embedded in the P3 component. Thus, the neural mechanisms of action inhibition initiated and peaked later in boxers than in either control group. Source analysis localized this brain activity to the anterior and posterior areas, most likely within the anterior cingulate gyrus in the prefrontal cortex and in the dorsal superior parietal cortex. Even though source localization is not a strength of the ERP technique, the large spatio-temporal separation of the modelled source and strong agreement with previous studies that found similar sources (Dias et al., 2003; Bekker et al., 2005) provide a sufficient margin of confidence in the reliability of these results.

The prefrontal cortex is critical for top-down control of executive functions and the temporal organisation of behavior. According to many authors, ACG activity is specifically involved in conflict monitoring and response inhibition (e.g., Ray Le, Huang, Constable, & Sinha, 2006). More generally, the anterior cingulate cortex is part of the core system for institution of task parameters, set maintenance, and response monitoring (e.g., Dosenbach et al., 2006). The dorsal parietal cortex contributes to this network, as it is modulated when people change their object-related motor plan during task switching (e.g., Rushworth, Paus, & Spila, 2001). Prefrontal activity and dorsal-parietal activity were delayed in boxers. Overall, we interpret this data as an indication of selective impairment of specific vulnerable mechanisms involved in response inhibition.

Even though our study is based on a cohort of professional boxers and there is evidence that the health/harm ratio in amateur boxing is different from that in professional boxing (e.g., Loosmore et al., 2007), we hope that the evidence provided here prompts careful consideration before directing young people toward combat sports that involve frequent head shocks, and for the development of more efficient safety measures such as helmets.

REFERENCES


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