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Long term effects of recreational SCUBA diving on higher cognitive function

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We investigated long-term effects of SCUBA diving on cognitive function using a battery of neuropsychometric tests: the Simple Reaction Time (REA), Symbol Digit Substitution (SDS), Digit Span Backwards (DSB), and Hand-Eye Coordination tests (EYE). A group ($n = 44$) of experienced SCUBA divers with no history of decompression sickness was compared to non-diving control subjects ($n = 37$), as well as to professional boxers ($n = 24$), who are considered at higher risk of long term neurological damage. The REA was significantly shorter in SCUBA divers compared to the control subjects, and also more stable over the time course of the test. In contrast, the number of digits correctly memorized and reordered (DSB) was significantly lower for SCUBA divers compared to the control group. The results also showed that boxers performed significantly worse than the control group in three out of four tests (REA, DSB, EYE). While it may be concluded that accident-free SCUBA diving may have some long-term adverse effects on short-term memory, there is however, no evidence of general higher cognitive function deficiency.

Active recreational SCUBA divers are estimated to represent 7 million people (PADI; Vann et al., 2005), with the biggest certifying agency, P.A.D.I, issuing over 500 000 certifications per year and the number of certified divers tripling in the last 20 years. Scuba diving per se, even when carried out according to standard rules, leads to bubble formation (Ljubkovic et al., 2011; Mollerlokken et al., 2011), which may be created in, or reach, the brain.

Despite this, so far studies on the long-term effects of SCUBA diving have focused on professional, commercial and military diving and very few studies have looked at recreational SCUBA divers (Slosman et al., 2004).

In professional divers, a decrease in cognitive abilities has been shown, such as decreased mental flexibility (Cordes et al., 2000), as well as lower verbal memory (California Verbal Learning Test), intelligence (Wechsler Abbreviated Scale of Intelligence), and sustained attention (Rapid Visual Information Processing test) in divers reporting memory and concentration loss (Taylor et al., 2006).

In recreational SCUBA divers, a study using magnetic resonance imaging (MRI) brain imaging showed lesion-like signals in the central nervous system in SCUBA diving instructors not present in control subjects (Tripodi et al., 2004). Similar results have been observed in groups of recreational divers (Knauth et al., 1997). The "morbidity" of such lesion-like signals is still debated since they have not been related to symptoms. Also, it has been shown that the spatial distribution of these white matter "lesions" has no vascular appearance which will match with gas emboli, but rather appears distributed in a comparable way to multiple sclerosis lesions that have no direct vascular origin (Balestra et al., 2004).

Another population at risk of long-term effects is combat sportsmen, in particular neurological and eye damage due to chronic sustained shocks. Studies indicate that professional boxers are more likely to develop cognitive deficits due to greater exposure to forceful injury-related blows over a longer period of time (Loosemore et al., 2008). Zazryn et al. (2006) showed that 27.1% to 93.4% of injuries involve the head. These include (a) acute neurological damage mainly caused by knock out, (b) post-concussion syndrome, and (c) chronic traumatic encephalopathy or "punch-drunk syndrome" (Heilbronner et al., 2009). The frequency of cerebral concussions leads to an increase of the neurological syndrome duration that may evolve into chronic traumatic encephalopathy (Heilbronner et al., 2009). Post-concussion syndrome is responsible for the long-term cognitive deficits because of multiple shocks over a short period (Grindel et al., 2001) which may explain the decrease in attention, concentration, memory and hand-eye coordination found among professional boxers (Jordan et al., 1996). Similarly, to divers, these lesion-like signals have a non-vascular origin (Haglund & Eriksson, 1993).

The aim of this study was to assess the long-term effects of recreational SCUBA diving on higher cognitive function and especially reaction time, attention and coding, short-term memory and coordination. To do so, a group of recreational SCUBA divers with no history of decompression sickness were compared to boxers and control subjects using a battery of neuropsychometric tests.

Methods

Participation in the study was on a voluntary basis. Experimental procedures were conducted in accordance with the Declaration of Helsinki and were approved by the Academic Ethical Committee of Brussels (Ethic committee B 200–2009-39). All participants gave their written informed consent prior to the experiment.

Control subjects were recruited from a student sample, with regular (4–5 times a week) non-traumatic physical activity. Before they participated in the study, they confirmed their eligibility (absence of cardiac or neurological disorders, no medication and no history of migraines). The SCUBA divers had to be less than 45 years old, have at least 200 dives with no history of decompression sickness (DCS) and no accounts of having ever felt dizzy or unusually fatigued after a dive which could possibly be undiagnosed DCS. Diving experience and diving habits were collected by a written questionnaire.

The boxers were either professional or competitive fighters with at least 5 years of experience, but without major head trauma (minor concussions usually lead to at least 3 months of not boxing). All boxers were declared “fit to fight” by the Belgian boxing federation medical standards at the time of the study.

The higher cognitive functions were tested by a computerized battery of tests (Neuroscreen, IDEWE, Belgium and Psychology Experiment Building Language). These tests are widely used and allowed to detect cognitive disturbances at an early stage and provide valid and versatile research tools for measuring executive functions (Baker, 1994; Michiels, 1999; Piper et al., 2012). The detailed description and procedures for these tests can be found in Balestra et al. (2007). The test battery consisted of four neuropsychometric performance tests:

The Simple Reaction Time test (REA)

This test is used to assess psychomotor speed (attention and reaction time). The subject is asked to push down on a button with the index of the hand he uses to write, as soon as a red square lights up. The light turns on 60 times after random time intervals (minimum 2.5 s – maximum 5.5 s). The mean reaction time and standard deviation (SD) of the whole session were calculated. To assess the fluctuation of the response time over the whole session, the stability of the reaction time was also calculated as 1/SD of the REA (Michiels, 1999).

The Symbol Digit Substitution test (SDS)

The test is used to assess individual associative speed (perception and coding). Briefly, nine digits are associated with nine simple symbols. Underneath that, the nine symbols are presented in a different order and the subject has to fill in, as quickly as possible, the corresponding digit. This test was repeated five times with changing combinations. The percentage difference between the expected and achieved values were calculated for each subject, where the expected value takes into account education level and subject age.

The Digit Span Backwards test (DSB)

This test measures the short-term memory and ability to concentrate. The test was carried out according to Balestra et al. (2007). The subject is presented with an incrementing number of digits which flash on a screen for 0.6 s each. He then has to enter them in reverse order by memory. Every time he succeeds, the number of digits to remember increases by one, and conversely. The test starts with two digits and goes up to a maximum of 20 digits. The percentage difference between the expected and achieved values were calculated for each subject, where the expected value takes into account education level and subject age.

The Hand-Eye Coordination test (EYE)

This test measures coordination. The subject has to follow, as well as possible, a sine curve presented on the screen with a calibrated joystick (Trail Making test). The position of the joystick is represented by a little square, which moves at a constant speed from left to right on the screen. The missed surface compared to the sine curve is calculated in terms of number of pixels. The mean score is then analyzed.

The whole testing procedure took on average 45 min. After a short training of each test, the test battery was administered only once, in order to avoid learning effects.

After testing with Kolmogorov–Smirnov and Shapiro–Wilk normality tests, results were analyzed using *t*-tests and Mann–Whitney U-test as appropriate. All statistics were performed using a standard computer statistical package, GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego, California, USA). To visualize changes, all data were compared to the control group values (baseline values).

All data are presented as mean values ± SD.

Results

In total, 105 subjects participated in the study: SCUBA divers ($n = 44$), boxers ($n = 24$) and control subjects ($n = 37$). Owing to computer storage errors, some of the tests were not useable for analysis. This resulted in only 39 SCUBA divers used in the analysis of the SDS and DSB tests, and 40 SCUBA divers and 21 boxers used in the EYE test analysis.

Demographics

The mean age of the group of SCUBA divers (see Table 1) was 32.98 ± 4.93 years (mean ± SD). Mean years of diving were 11.70 ± 6.20 years and mean number of dives was 658.4 ± 510.20. “No-decompression diving” was defined as “dives not requiring decompression stops according to the dive computer used by the diver”. For the boxers, the mean age was 30.63 ± 8.65 years. For the control group, the mean age was 30.51 ± 7.79 years.

The REA test

The SCUBA divers showed a significantly faster mean REA compared to both the control subjects

(235.1 ± 49.10 ms vs 280.6 ± 64.81 ms, $P < 0.05$) and the boxers (355.2 ± 48.68 ms, $P < 0.001$). The group of boxers had a significantly slower REA than the control group (difference 65 ms, $P < 0.001$) (Fig. 1(a)).

The stability of the simple reaction time was found significantly better for the SCUBA divers compared to the control subjects (4.99 ± 1.66/ms vs 2.62 ± 1.10/ms, $P < 0.001$). The stability of the simple reaction time for the boxers (1.97 ± 0.51/ms) was significantly lower compared to both the control ($P < 0.05$) and the group of SCUBA divers ($P < 0.001$) (Fig. 1(b)).

The SDS test

The percentage difference between the expected and the achieved values of the SDS test for the three groups was 2.36 ± 0.32% for the SCUBA divers, 2.35 ± 0.48% for the control subjects and 2.50 ± 0.60% for the boxers, respectively. No statistically significant difference could be found between the three groups (Fig. 2).

The DSB test

For the DSB test, no significant difference was observed between the samples of boxers and divers. However, the length of the sequence that the SCUBA diving sample was able to correctly remember was shorter compared to the one memorized by the control subjects (5.93 ± 1.61 vs 7.30 ± 2.00 digits, $P < 0.001$). The same was observed for the group of boxers compared to the control subjects (6.11 ± 1.33 vs 7.30 ± 2.00 digits, $P < 0.05$). There was no significant difference between the test scores of the SCUBA divers and boxers (5.93 ± 1.61 vs 6.11 ± 1.33 digits) (Fig. 3).

Table 1. Demographics of test subjects and controls. “No deco diving” = dives which do not required mandatory decompression stops according to the decompression algorithm used

$n = 44$	Mean	SD
Age (years)	32.98	± 4.93
Dive experience = number of dives	658.4	± 510.20
Dive experience = years of dives	11.7	± 6.20
Average depth > 30msw	343.49	± 344.31
Average depth < 40msw	97.56	± 93.78
Average fraction of dives > 30msw	55.02	%
Average fraction of dives > 40msw	15.63	%
Computer use (% of divers)	100	%
No-decompression diving (% of divers)	100	%
Systematic safety stop observed	97.72	%

The EYE test

No significant difference was found between the SCUBA divers and control groups for the EYE test (1983 ± 778.6 vs 1780 ± 551.6 pixels). However, a significantly worse results score was observed in boxers compared to the control subjects (2180 ± 709.1 vs 1780 ± 551.6 pixels, $P < 0.05$) (Fig. 4).

Discussion

To critically evaluate the effects of long term recreational SCUBA diving on higher cognitive functions, we used a battery of computer-administered neuropsychometric tests to compare SCUBA divers with both a control group of non-diving, healthy young volunteers and a group of subjects with a high likelihood of non-vascular cerebral “damage” (boxers).

Our study showed that the SCUBA divers had significantly worse performance in DSB test, pointing to some tendency of short-term memory deficits. On the other hand, we observed a faster and more stable REA compared to the other groups. Professional boxers had significantly worse results in EYE, REA and Reaction Time Stability as well as the DSB (DSB) test compared to the control group.

Interestingly, there was no significant difference between the DSB scores of the SCUBA divers and boxers, who both performed significantly worse than the control group.

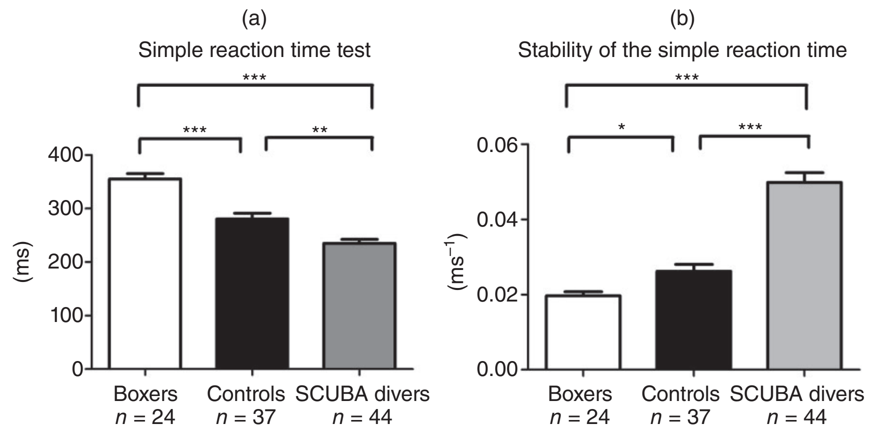

Fig 1. Simple reaction time test and stability. (a) Simple reaction time (b) stability of the simple reaction time. Data are presented as mean ± standard deviation (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$).

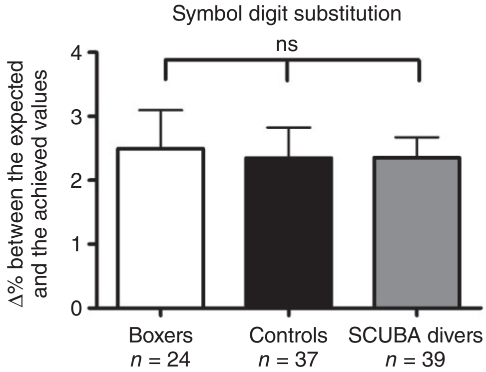

Fig 2. The percentage difference between the expected and the achieved values of the Symbol Digit Substitution, comparison between groups. Data are presented as mean ± standard deviation. There is no significant difference between the three groups (ns = $P > 0.05$).

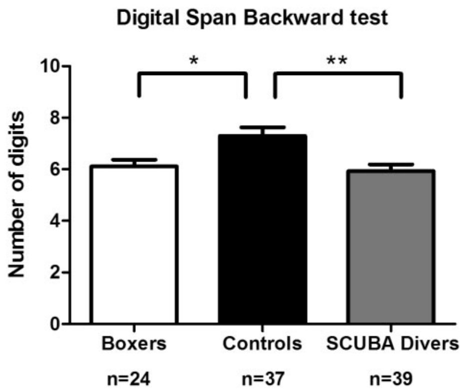

Fig 3. Digit Span Backwards test, comparison between groups. Data are presented as mean ± standard deviation, (*$P < 0.05$, **$P < 0.01$).

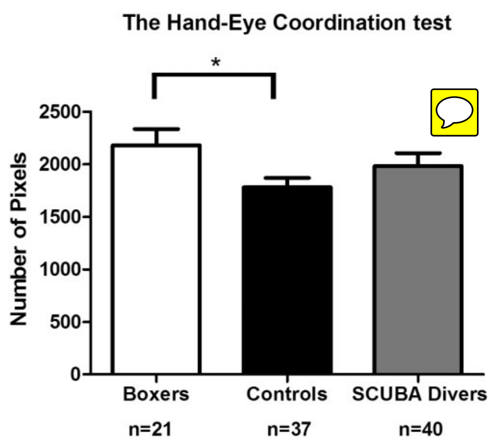

Fig 4. EYE test (hand-eye coordination) comparison between groups. Data are presented as mean ± standard deviation. (*$P < 0.05$).

Even though the results in DSB between boxers and SCUBA divers might be considered as comparable, the mechanism of "damage" leading to such alteration is probably different. Combat sports practitioners and in particular professional boxers have been shown to be at higher risk of long-term neurological damage (Grindel et al., 2001; McCrory et al., 2007).

It has been shown that mechanical effects in professional boxers are paramount, translating in repeated concussions, edema and hemorrhages (Heilbronner et al., 2009); in addition, there is evidence that professional boxers may have altered cerebral hemodynamic function due to the mechanical trauma caused by repetitive subconcussive head impacts (Bailey et al., 2013). These are often accompanied by localized hypoxia, when blood clots or swelling restrict the circulation and thus oxygen delivery to brain cells (Trettin, 1993). It has been also shown that unrecognized head injuries on the ringside may lead to cognitive impairments in boxers (Moriarity et al., 2012). In addition, such repetitive brain trauma associated with cognitive function impairment might be linked to a later evolution of different diseases such as dementia and Parkinson's disease by modification of anatomical part of the brain (Costanza et al., 2011). These mechanisms are thus capable of explaining short- and/or long-term partial impairment of higher cognitive function and might also explain the results of our findings in the boxers group.

For divers, two mechanisms of damage have to be discussed. On the one hand, there is a direct effect from gas toxicity, with nitrogen and oxygen increase as well as associated ventilatory and cardiovascular responses. On the other hand, there are also chronic "toxic" effects to consider, linked to brain plasticity as an adaptation mechanism to deal with this extreme environment, as well as the effects of asymptomatic DCS occurrence.

SCUBA divers are repeatedly exposed to unnatural environments including barometric changes. Even in the recreational SCUBA diving setting, at depths shallower than 40 meters, the partial pressure of nitrogen is up to five times higher than at the surface. This has important effects on cognitive function as demonstrated by nitrogen narcosis (Balon et al., 2003; Lavoute et al., 2005; Rostain & Balon, 2006). Jokingly referred to as the Martini's Effect, which states that the perceived effects of narcosis at depth are similar to a glass of Martini for every 15 meters of depth, nitrogen narcosis affects time perception, reaction speed and ability to think, calculate and react (Levett & Millar, 2008). It has been implicated in many SCUBA diving accidents (Levett & Millar, 2008). Despite the precise mechanism still being debated, animal studies have shown that nitrogen narcosis is mainly caused by the activation of GABA receptors (Rostain & Balon, 2006). In addition, some research suggests that other neurotransmitters, either inhibitory or excitatory, are also involved (Rostain & Balon, 2006; Lavoute et al., 2008).

In terms of neurotoxic effects, one should also consider the risks of increased partial pressure of oxygen at depth (Fock & Millar, 2008). This is especially relevant while diving with enriched air nitrox, a nitrogen-oxygen mixture with oxygen content higher than 21%. Such effects of inert gas narcosis on brain performance have been confirmed in human subjects by measurement of Critical Flicker Fusion Frequency (Lafere et al., 2010; Balestra et al., 2012).

The long-term effects of SCUBA diving on short-term memory have been previously shown in studies involving professional divers (Cordes et al., 2000; Taylor et al., 2006), but these were more specifically linked to the techniques used in commercial diving (namely surface oxygen decompression and mixed gas bounce diving) (Taylor et al., 2006). It is thus noteworthy that comparable findings may apply to recreational divers as well.

In recreational SCUBA divers, long-term effects have been demonstrated in terms of ventilatory impairments (Tetzlaff et al., 1998; Lemaitre et al., 2006) and autonomic responses to cardiovagal variation (Barbosa et al., 2010). Regarding long-term effects on higher cognitive function, the speed, flexibility and attention tasks (Slosman et al., 2004) were shown to be affected.

It has been shown in rat models that repeated GABA receptor stimulation significantly influences brain plasticity (Mott & Lewis, 1992). It can be speculated that for SCUBA divers, the repetitive unpredictable activation of different neuronal receptors and changes in neurotransmitters levels may lead to adaptation of neuronal function, commonly known as plasticity. This may be further supported by the fact that repeated exposures to nitrogen high partial pressures have neurotoxic effects in rats (Lavoute et al., 2012).

Alternatively, the higher cognitive function changes observed in recreational SCUBA divers may be linked to pathophysiological changes in brain anatomy (Abe et al., 1998). Brain MRI studies have shown that lesion-like white matter signals can be found even in asymptomatic SCUBA divers with no history of DCS (Knauth et al., 1997). Nevertheless, no biochemical signs of brain injury were found after uneventful diving, which suggests the pathophysiology may be more related to (asymptomatic) diving accidents than to the dive itself (Stavrinou et al., 2011). Depths and ascent rate chosen in this study was very conservative and other research has shown that brain lesions were significantly associated with unsafe diving practices such as rapid ascent rate (Tripodi et al., 2004).

These points to the decompression models used in recreational SCUBA diving as still not conservative enough to prevent long-term effects. For instance, it may be preferable to use the presence and time course of venous gas emboli (VGE) post-dive as an indicator of decompression stress during the development of a decompression algorithm, rather than the presence or absence of decompression sickness symptoms. These VGE have been shown to vary significantly from diver to diver for a same profile (Blogg & Gennser, 2011) and may better reflect the individual "resistance" to decompression stress. This is especially important considering the high incidence of patent foramen ovale in the population (roughly one in four) which may permit VGE to enter the arterial circulation and reach the brain (Germonpre et al., 2005; Lisignoli et al., 2007).

In contrast to the worse performance in short-term memory, we have observed a better performance in reaction time and reaction time stability in SCUBA divers. This might be the result of the life style of the subjects as divers are generally considered to be of an adventure-loving, risk-taking predisposition (Watson & Pulford, 2004). However, if this were the case, we would have expected a worse stability of the reaction time, not a better one. This implies that the divers have indeed a better performance of the relevant neuronal circuits, and that they do not "just guess" or react instinctively. Consequently, better results, sometime equal and just one test presenting worse results for the divers sample can hardly depict a significant impairment of everyday life.

Perspective

The long-term effects of recreational SCUBA diving were investigated using a battery of neuropsychometric tests, comparing them with those of professional boxers and control subjects. The results suggest that there might be some long-term effects of recreational SCUBA diving on short-term memory even in asymptomatic divers with no history of DCS. REA and stability of the simple reaction time were significantly better.

These findings underline the need to further investigate short and long term effects of SCUBA diving on brain performance and possibly refine the decompression models used.

Key words: memory, Central Nervous System, neuropsychology, CNS, injury, boxing, adverse effects, physiology.

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