A comparison of simple reaction time, visual discrimination and critical flicker fusion frequency in professional divers at elevated pressure

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Abstract

(Tikkinen J, Wuorimaa T, Siimes MA. A comparison of simple reaction time, visual discrimination and critical flicker fusion frequency in professional divers at elevated pressure. *Diving and Hyperbaric Medicine*. 2016 June;46(2):82-86.)

Introduction: Inert gas narcosis (IGN) impairs cognitive performance and some divers are more susceptible to IGN than others. We compared the sensitivity of two reaction time tests to detect changes in performance at pressure and compared these results with critical flicker fusion frequency (CFF) changes at the same ambient pressures.

Methods: The study assessed simple reaction time (RT), mean time correct of the discrimination reaction time (MTC) and CFF in 30 professional divers breathing air at 101 kPa and 608 kPa in a hyperbaric chamber.

Results: RT and MTC increased at 608 kPa by 5.1 ± 9.4% ($P = 0.04$) and 7.3 ± 12.3% ($P = 0.01$) respectively. RT decreased to pre-compression level after decompression and MTC decreased to a level lower than pre-compression ($P < 0.001$) values. CFF increased by 2.5 ± 2.8% ($P < 0.001$) at 608 kPa. CFF decreased to pre-compression level after decompression. An increase in CFF was inversely correlated with a decrease in RT ($r = 0.38$, $P = 0.04$) and in MTC ($r = 0.43$, $P = 0.02$) at 608 kPa.

Conclusions: Response speeds of the same subjects were impaired in both reaction time tasks at 608 kPa, whereas CFF increased at depth. An association between changes in response times and changes in CFF suggests that divers susceptible to IGN may also be susceptible to the effects of elevated oxygen partial pressure. If this holds true, the future selection of professional divers could be improved by the use of simple cognitive tests.

Key words

Narcosis; nitrogen; performance; psychology

Introduction

The impairment in human cognitive performance while breathing compressed gases at increased ambient pressure has been explained on the basis of the raised partial pressure of inert gases such as nitrogen, termed inert gas narcosis (IGN).[1] Measurable changes in diver performance have been shown from pressures as low as 203 kPa (2.0 atmospheres absolute).[2] Some divers seem to be more susceptible to IGN than others, and its onset pressure varies among individuals.[3]

The finding that human performance deteriorates due to elevation of ambient pressure and increased partial pressure of nitrogen is explained by the slowed processing model.[4] According to this model slowing is primarily a result of decreased arousal and is manifested by an increase in simple reaction time (RT), slowing in other tasks such as abstract reasoning tests and sorting cards.[5–7] However, the strategy used to perform a task also changes under IGN and it is considered to be a response to slowing. For example, speed can be increased by shifting speed-accuracy trade-off setting, allowing more mistakes. It has been demonstrated that rehearsal strategies also may be modified by IGN but can be manipulated experimentally.[8] Controlling for the strategies during experiments is important in revealing the slowing of psychomotor performance by IGN. Reaction time is a commonly used parameter in experiments attempting to quantitate IGN. It measures total decision-making time that constitutes total information processing. Total information processing also involves higher-order cognitive functions, such as learning. Skill and procedural learning become confounders when the complexity of the task increases.[9] Repeating the same task improves the results and comparing the results obtained at different ambient pressures becomes challenging.

There is a long-standing experience with the critical flicker fusion frequency (CFF) in the evaluation of the effect of psychoactive drugs,[10] and as a measure of the ability to discriminate sensory data.[11] CFF appears to be a simple and reliable way of assessing changes in cortical arousal,[12] and has been demonstrated to be stable to repeated tests.[13]

The results of studies investigating the relation between ambient pressure, composition of inhaled gases and CFF have been somewhat ambiguous. Breathing normobaric oxygen (O_2) increased CFF in one study,[14] whilst in another CFF was unchanged during 71 kPa O_2 exposure, decreased at 141 kPa O_2 but increased at 283 kPa O_2.[15] In a study of divers performing wet air dives at a depth of 33 metres' fresh water (mfw), CFF was reported to initially increase and then decrease, this decrease being sustained after decompression.[16] Similar results were reported in another study of wet air dives.[17]

The aims of the present study were to compare the sensitivity of two reaction time tests to detect changes in performance at pressure and to compare these results with CFF changes at the same ambient pressures in order to evaluate the potential of the CFF test to detect IGN. We also assessed whether there were any correlations within individuals between the changes in the cognitive performance tests and CFF.

Methods

SUBJECTS

The study protocol was approved by the Ethical Committee of the University Hospital of Helsinki and the Headquarters of the Finnish Defence Forces. We studied 30 professional male divers from the Finnish Navy and the Coast Guard aged from 23 to 50 (mean 35 ± 8) years. The divers gave their written informed consent to participate following a detailed explanation in writing of the study procedures. Divers abstained from strenuous exercise, diving, alcohol, nicotine products,[18] medicines and caffeine[19] for at least 24 h before the experimental trial.

Divers were exposed to a pressure of 608 kPa (50 metres' sea water, msw) in a dry hyperbaric chamber as part of their annual medical examination. Compression was at a rate of 9 ± 1 msw·min^{-1} and the target pressure was reached in 6 ± 1 min. Decompression was based on a 51 msw/15 min bottom time table (Finnish Navy, DCAP-FINN). Decompression stops were made at 9, 6 and 3 msw for 7, 2 and 8 min, respectively. Temperature, oxygen (PO_2) and carbon dioxide (PCO_2) partial pressures were measured during the simulated dives, with the PO_2 between 21.0 and 21.5% and the PCO_2 under 1000 ppm by ventilation and Haux absorbers. The temperature varied from 18 to 32^{O}C during the compression and decompression of the chamber.

Subjects, in pairs, did three 'dives' at the same time of day during which, whilst seated at rest, they performed either one of two reaction time tests or were tested for their CFF. This was in order to minimize the exposure time and to avoid fatigue influencing the results. The interval between the tests varied from two to four weeks. Simple RT was performed on the first test day, a discrimination reaction time test on the second day and CFF on the final test day.

SIMPLE REACTION TIME

We utilized the reaction time test form S1 from the Schuhfried Vienna Test System RT (reaction test).[20] A simple visual signal was shown on an LCD monitor; the subjects were required to react to the signal by pressing the correct trigger button. The reaction time is the time interval that elapses between a signal and the start of the mechanical response movement, i.e., when the subject lifts his finger from the rest button. The visual signal was shown 28 times at each pressure condition, the test taking 3 to 5 min to complete.

The divers practiced the test once at ambient pressure, in the hyperbaric chamber once and went through short training sequences before commencing the actual tests. We then measured the RT in the chamber before compression, at 608 kPa and immediately after decompression. The mean reaction time values were used only from those reactions that were correct and complete. In order to normalize the distribution of the raw reaction time scores the Box-Cox transformation was carried out.[21] The results were presented as milliseconds (ms). An increase of 16% or more in the values was considered as important.[5]

DISCRIMINATION REACTION TIME

We utilized the Cognitrone trial form S7 from the Schuhfried Vienna Test System.[22] A pair of figures was shown on an LCD monitor; the subjects, after comparing the figures, decided whether they were identical or not by pressing the green button for identical or the red one for not identical. The subjects performed the trial seven times. The divers were expected to achieve their maximum response speed by the fifth trial.[23] During a trial, 50 pairs of figures, 25 pairs of identical and 25 pairs of different figures, are presented twice in immediate succession in a random order. It took 3 to 7 min to complete a test. The divers were instructed to work as accurately and quickly as possible.

A minimum criterion of 85% correct answers for both identical and different figures was used. Short training sequences were performed before each of the actual trials at ambient pressure, 608 kPa and immediately after decompression. The variable 'mean time correct' (MTC) of the discrimination reaction time was calculated. This value represents the time spent recognizing that the figures are different. The trials were performed in the chamber four times before compression, once at 608 kPa pressure and once immediately after decompression. The MTC were used only from those reactions that were both correct and complete. Results are presented in seconds (s). An increase of 19% or more in the values was considered as important.[22]

CRITICAL FLICKER FUSION FREQUENCY

Critical flicker fusion frequency (CFF) thresholds were measured by the FLIM test from the Schuhfried Vienna Test System.[24] Visual stimulation with a luminous diode was achieved through the flicker fusion unit (model 64031, Schuhfried Vienna Test System). The frequency of flickering light was increased in steps of 0.1 Hz from 10 Hz until the subject pressed a button as an indication of fused light. Similarly, the frequency was decreased stepwise from 80 Hz until the subject perceived the light to flicker. CFF was calculated as the average of eight fusion and flicker frequencies. It took 5 to 12 min to complete a test.

STATISTICS

The IBM SPSS 20 computer package was used for statistical analyses. The results are presented as mean ± standard deviation (SD). The Shapiro-Wilk test was used to assess the

Table 1

The mean ± SD of transformed reaction time (1/RT), transformed mean time correct of the discrimination reaction time (1/MTC) and actual critical flicker fusion frequency (CFF) for 30 professional divers measured in a hyperbaric chamber before compression, at 608 kPa and after decompression; * $P = 0.04$; † $P = 0.01$; ‡ $P < 0.001$

Test	**Ambient pressure** (kPa)		
	101.3 (pre-compression)	608	101.3 (post-compression)
1/RT	0.0037 ± 0.0006	0.0035 ± 0.0006*	0.0038 ± 0.0007‡
1/MTC	1.04 ± 0.16	0.98 ± 0.18†	1.13 ± 0.18‡
CFF	38.1 ± 1.7	39.0 ± 2.2‡	37.9 ± 2.1‡

Figure 1

Individual changes in simple reaction times (RT) and in mean time correct of the discrimination reaction time (MTC) of 30 professional divers after compression to pressure of 608 kPa in a hyperbaric chamber compared to baseline; lines of identity drawn to mark an increase of 16% or more in RT and of 19% or more in MTC

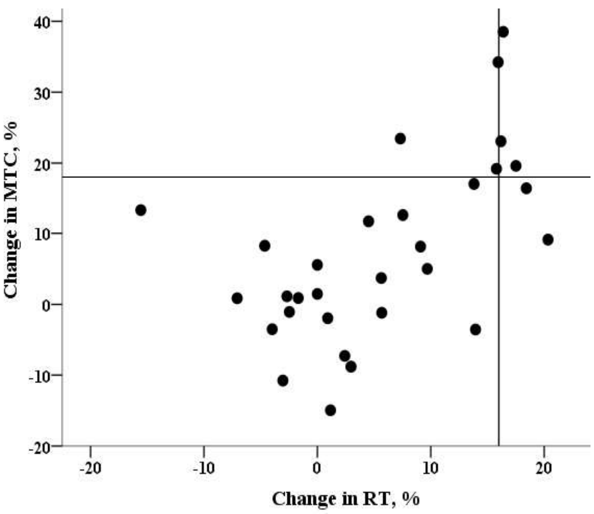
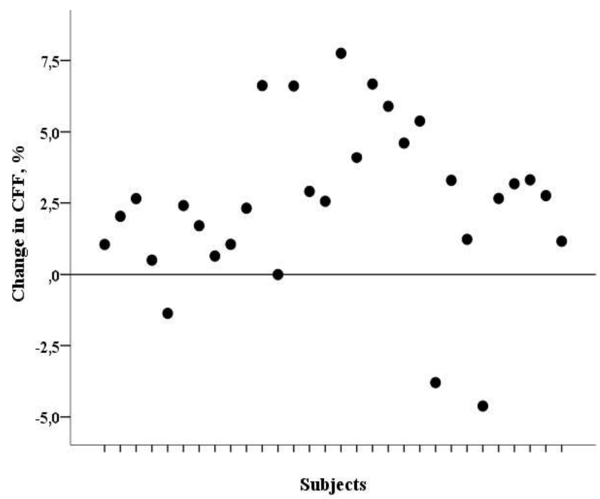


Figure 2

Individual changes in critical flicker fusion frequencies (CFF) of 30 professional divers after compression to pressure of 608 kPa in a hyperbaric chamber compared to baseline



normality of the distribution of RT, MTC and CFF. Skewed values (RT, MTC) were transformed by 1/x transformation to allow parametric statistical analyses. The association of the ambient pressure and time values from the three separate trials was assessed by repeated measures analysis of variance (ANOVA) and the post hoc analysis by Bonferroni test. Associations between transformed RT, transformed MTC and CFF were calculated by using Pearson's correlations coefficient. A pre-study power analysis was not performed. A *P*-value less than 0.05 was considered as significant.

Results

REACTION TIME AND DISCRIMINATION REACTION TIME

The means ± SD of the transformed RT and MTC data and the actual CFF values are shown in Table 1. RT, MTC and CFF all increased significantly at 608 kPa by 5.1 ± 9.4%, 7.3 ± 12.3% and 2.5 ± 2.8% respectively. There was a significant effect of experimental conditions on the RT values ($F(2, 58) = 9.89$, $P < 0.001$). Mauchly's test indicated that the assumption of sphericity had not been violated ($\chi^2(2) = 1.89$, n.s.). Post hoc comparisons revealed that the RT values were elevated at 608 kPa compared to the pre-compression values ($P = 0.04$) and the values measured after decompression ($P < 0.001$). The pre-compression and after-decompression values did not differ from each other.

The experimental conditions also had an effect on MTC ($F(2, 58) = 27.36$, $P < 0.001$); sphericity was not violated ($\chi^2(2) = 2.82$, n.s.). Post hoc tests showed that MTC values were elevated at 608 kPa compared to both pre-compression and post-compression values ($P = 0.01$ and $P < 0.001$ respectively). After decompression MTC was lower than pre-compression MTC ($P < 0.001$).

The changes in RT and MTC are shown in Figure 1. There were seven divers with an increase of 16% or more in RT at 608 kPa.[5] Similarly, there were six divers with an increase of 19% or more in MTC[22] at 608 kPa. Five of the divers had an increase of 16% or more in RT and an increase of

19% or more in MTC. Maximal increase was 20% in RT and 38% in MTC.

CRITICAL FLICKER FUSION FREQUENCY

There was a statistically significant effect of the experimental condition on CFF of the divers ($F(2, 58) = 16.30$, $P < 0.001$). CFF increased at 608 kPa compared to pre- or post-compression values ($P < 0.001$ for both). The pre-compression and post-decompression values did not differ from each other. The individual changes in CFF compared with pre-compression CFF at 608 kPa and post-compression are plotted in Figure 2.

Actual RT values were not associated with MTC values ($r = 0.11$, ns), whilst CFF values were not associated with RT, or MTC values ($r = -0.33$ and $r = 0.22$ respectively; both n.s.). A significant association between the changes in RT and the changes in MTC between the pre-compression values and those at 608 kPa was found ($r = 0.56$, $P = 0.001$). The change in CFF was associated with both the change in MTC and with the change in RT ($r = 0.43$, $P = 0.02$ and $r = 0.38$, $P = 0.04$ respectively).

Discussion

We observed a reduction in psychomotor performance similar to that found in our previous study using similar tasks at the same (608 kPa) pressure condition.[5,22] The complexity of the responses to be performed influenced the results in that MTC changed more under pressure than simple reaction time, again, in keeping with previous studies. The return of MTC to less than pre-dive values is possibly due to a learning effect. The deterioration in performance was of short duration, having recovered immediately post compression. We hypothesise that the increase in reaction times is caused by IGN. This obviously has importance when performing complex tasks during a dive or in a hyperbaric chamber.

The pressure-related changes in CFF could be a result of modified neuronal activation due to selective and transient activation of the central nervous system resulting from a changed tissue oxygen partial pressure (PO_2). Unlike a previous study, in which the observed decrement in CFF was sustained after decompression,[16] post-compression CFF in our study had returned to pre-compression levels. However, this difference post-compression could be because of different environmental conditions, including differing workloads, in the two studies; ours was with subjects seated in a dry chamber, whereas the previous study was of actual scuba dives to 33 msw.[16] Other factors, such as CO_2 retention, may also have a role and could explain the initial increase in CFF observed in the scuba divers.[25] Also physical activity of a diver is likely to be lower in a hyperbaric chamber than during a wet dive. Fatigue has been demonstrated to have an effect on CFF.[26]

A previous study has demonstrated that there is an association between CFF and discrimination reaction time.[27] We also observed an association between changes in CFF and changes in the simple and discrimination reaction times at 608 kPa, but not in the absolute values of these parameters. Our study supports the concept of individual susceptibility to IGN. If a subject is more susceptible to the impairment of performance due to increase in ambient pressure, could he also be more susceptible to increased arousal caused by an increased PO_2 or some other variable? Identifying those individuals might improve selection of divers for training and for deeper and more demanding diving tasks.

Some limitation of the study should be pointed out. CFF appears to be sensitive to a variety of extrinsic and intrinsic factors, e.g., ambient temperature, systolic blood pressure and personality have been shown to affect CFF.[28–30] Control for these factors is difficult in a hyperbaric chamber. Task practice may result in improved performance, and many cognitive tasks involve stimulus-response pairings which can be learned. The discrimination reaction test is an example of such a task.[22]

Conclusion

Breathing air at 608 kPa increased the simple reaction time and discrimination reaction time. Response speeds in some of the subjects were impaired in both tasks. The simple reaction time decreased to pre-compression level after decompression and the discrimination time to a level lower than pre-compression values, possibly because of a learning effect. CFF increased at depth then decreased to pre-compression level after decompression. An association between changes in response times and changes in CFF was observed. This suggests that divers susceptible to IGN may also be susceptible to the effects of elevated PO_2. If this holds true, the future selection of professional divers could be improved by the use of simple cognitive tests. Further studies are needed to evaluate these findings.

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Conflicts of interest: nil

Submitted: 10 June 2015; revised 15 February and 23 March 2016
Accepted: 24 March 2016

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