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Cognitive impairment during 5 m water immersion

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Dalecki M, Bock O, Schulze B. Cognitive impairment during 5 m water immersion. *J Appl Physiol* 113: 1075–1081, 2012. First published August 9, 2012; doi:10.1152/japplphysiol.00825.2012.—Experimental data document that human cognition remains intact down to 6 m water immersion. This, however, is difficult to reconcile with introspective observations from experienced divers, who report cognitive impairments. We hypothesized that the discrepancy might be related to the fact that previous experiments assessed abstract cognitive skills, such as mental arithmetic, which might be less sensitive to immersion than performance-related cognitive skills, such as planning of behavior that is adequate for a given situation. Moreover, previous studies did not control for the effects of water viscosity on subjects' response times. To address these issues, the present study evaluated performance-related cognitive skills based on subjects' isometric responses. Forty-eight subjects were tested in 5 m under water and on dry land using multiple choice reaction tasks, a tracking task, and a combination of both. Sustained attention was also registered, and subjective workload was assessed by questionnaire. We found that a subject's cognitive performance was degraded under water by 9%, independent of task type and equally under single- and dual-task conditions. Sustained attention was reduced under water by 11% and tracking by 48%. The observed deficits were not correlated, which suggests multiple independent effects of immersion. Our findings support the hypothesis that performance-related cognitive skills are affected already by shallow-water immersion. Since no such deficits were observed in a companion study just below the water's surface, the present findings are probably due to increased ambient pressure.

diving; attention; tracking performance; simulated weightlessness; astronaut training

ACCORDING TO PREVIOUS RESEARCH, human cognitive abilities remain largely intact during water immersion down to 6 m depth but degrade dramatically at depths of 15-30 m (16, 23). The impairment is probably related to nitrogen narcosis (1), since substitution of nitrogen by helium and/or hydrogen is an effective countermeasure (2). However, other factors seem to play a role as well, since cognitive deficits under water are more pronounced than those in a hyperbaric chamber with the same air pressure (1, 18, 32). The additional factors may include cardiovascular responses to pressure and temperature, spatial disorientation in the absence of compelling visual and tactile cues, as well as anxiety in an unfamiliar and potentially dangerous environment.

Experimental data that document intact cognition down to 6 m water immersion are difficult to reconcile with introspective observations from experienced divers. In the European Space Agency's (ESA's) astronaut training facility, where space mission activities are routinely practiced at 3–10 m under water (8), working divers often notice that their cognitive abilities are poorer than on land, e.g., when they have to remember sequences of actions or must handle tools. We asked 10 ESA working divers to judge their cognition under water with respect to that on land using a scale from 1 (distinctly improved) to 5 (distinctly degraded). Seven divers responded 4 (slightly degraded), and the remaining three divers responded 3 (unchanged). This is significantly different from the null hypothesis that all divers report 3 [unchanged; $\chi(1) = 10.77$; $P < 0.01$]. From this, we concluded that professional divers are mostly aware of a moderate cognitive degradation under water.

The present study addresses this discrepancy between objective data and subjective observations. We hypothesize that the abstract cognitive skills assessed in previous diving studies, such as mental arithmetics, are less sensitive to immersion than performance-related cognitive skills, such as planning of behavior that is adequate for a given situation. Although some earlier studies did use complex behavioral tasks (3, 16), their interpretation is encumbered by the fact that the observed deficits may reflect not only cognitive decay but first and foremost, response slowing due to water's high viscosity. The confounding effects of viscosity can be overcome by examining motor skills in hyperbaric chambers (1, 3, 18, 32), but this approach also eliminates detrimental factors that only act under water (see above). Our present work therefore explores another avenue: subjects are tested under real water immersion, but their motor responses are largely isometric, such that water's viscosity plays a minor role.

In an earlier experiment (12), we have immersed the subjects' head only 20 cm below the water's surface. Visual targets were sequentially presented in one of four possible positions, and upon target appearance, subjects had to release a central button to depress the spatially matching peripheral button. We registered the release time (RT) of the central button, which unlike the response time at the peripheral button, required no appreciable hand movement and thus was little affected by viscosity. We observed no performance decrements on this task at 20 cm immersion and now expand this work to 5 m immersion. We also vary task complexity to capture not only subjects' decision-making ability but also their visuospatial and motor-planning skills, in accordance with previously established procedures (7). Additional tests controlled for subjects' workload, sustained attention, and anxiety. To explore the role of spatial disorientation, subjects were tested in different postures with respect to Earth's gravity.

METHODS

Subjects and setup. Forty-eight right-handed volunteers participated (46 males and two females aged 35.3 ± 9.9 yr, height 180.5 ± 6.6 cm, weight 81.1 ± 11.4 kg). They had no prior experience in sensorimotor research and no history of vestibular or sensorimotor deficits and signed a written, informed consent statement before participating. All subjects held a current, valid diving certification and had to finish 25 dives or more before participating in the experiment. The study was preapproved by the Ethics Committee of the German Sport University.

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As Fig. 1 illustrates, subjects wore a commercial diving jacket that was fixed to an aluminum frame at the bottom of a diving pool (20 × 20 m with a depth of 5 m). Frame orientation changed among subjects, such that 12 were tested in an upright posture (as in Fig. 1), 12 horizontally facing down, 12 horizontally facing up, and 12 vertically head-down. Across postures, the subject's head was between 3 and 4 m below water level. Air supply at ambient pressure was provided by conventional Scuba equipment, connected to a 12-l tank with pressurized air. Subjects wore a standard diving mask and a 7-mm neoprene suit to prevent hypothermia. Seventy-five centimeters ahead at eye level, they saw a 15-in. liquid crystal display screen on which experimental tasks were displayed. Water temperature was 26°C.

Control tests under dry conditions were conducted in an identical setup, except that subjects wore no diving equipment except for the diving jacket, which was fixed to a wall such that subjects remained in a stable, upright position. Note that on land but not in water, spatial orientation was facilitated by tactile cues about the gravitational vertical derived from contact with the jacket and the floor.

Experimental tasks. In the reaction-time tasks, subjects depressed the central button of a five-button box (see Fig. 1) with their left index finger. Curved targets were presented in random sequence to the left, right, top, or bottom of the screen center, with a display time of 100 ms and intertarget intervals of 500–1,500 ms. Subjects were instructed to release the central button as quickly as possible after target appearance and to depress the corresponding peripheral button. In task 4RT, targets and buttons were spatially congruent, e.g., the left target called for depressing the left button. In task 4RT-90, buttons were rotated by −90° with respect to the targets, e.g., the left target called for depressing the top button. In task 4RTtap, targets and buttons were spatially congruent, but subjects had to depress the button four times in a pre-established rhythm. Different rhythms (100–100-300–100 ms, 100–300-100–100 ms, and 300–100-100–100 ms) were used in different episodes of the experiment to minimize motor learning, and each rhythm was practiced before data collection started. Task duration was 120 s for 4RT and 150 s for 4RT-90 and 4RTtap. The same reaction-time tasks had been used before in a study aboard the International Space Station (7).

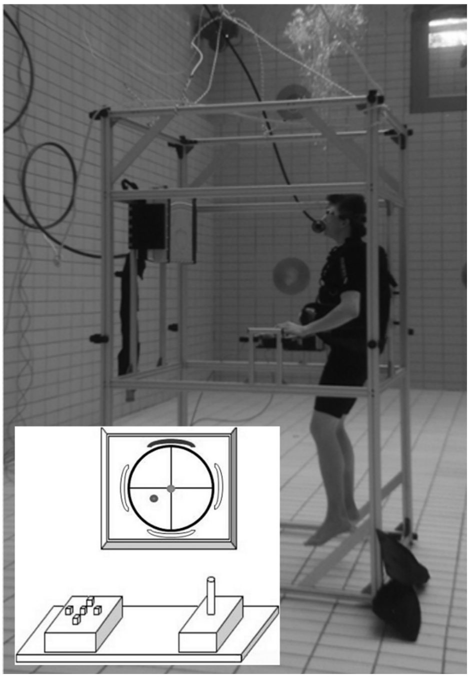

Fig. 1. Experimental setup under water. Subjects were fixed in a frame at 5 m depth in a diving pool, facing a liquid crystal display screen at eye level. They executed with their right hand an isometric tracking task and with their left hand, different 4-choice reaction tasks and a sustained attention task. The inset shows display, tracking stick, and reaction box from the subjects' perspective. With the subjects' right hand on the shank of the isometric joystick, they applied forces of varying magnitudes and directions to it, to keep a cursor (dark gray dot) as accurately as possible in the screen's center (light gray dot).

In the tracking task, subjects grasped with their right hand the shank of an isometric joystick, which was the same as in our previous studies (11, 12, 14, 24). Subjects applied forces of varying magnitudes and directions to it, to keep a cursor as accurately as possible in the screen's center. The relationship between the x and y positions of joystick and cursor followed a first-order divergent function (17) with added noise, and the cursor therefore moved with increasing speed toward the screen periphery if the joystick was simply held still. Whenever the cursor departed from the center by more than 7 cm, a warning sound marked a "loss of control", and the tracking task was discontinued; subjects then had to release the joystick, which returned the cursor to the center, and to resume tracking. Task duration was 60 s if tracking was performed alone. The same divergent tracking function had been implemented in previous spaceflight studies (7, 20–22); however, those studies used a regular displacement joystick, whereas we opted for an isometric joystick to minimize the effects of water's viscosity.

In the dual task, subjects performed the three reaction-time tasks concurrently with the tracking task. Task duration was the same as for the corresponding single RT tasks.

The sustained attention task was a computerized version of the d2 test (9). Subjects' left index finger rested on the left button and their right index finger on the center button of the response box. They saw a sequence of nine letters (d and p), each followed by 0, 1, or 2 superscript commas and 0, 1, or 2 subscript commas (e.g., d"). Their task was to depress the left button when seeing the letter d surrounded by two commas (regardless if on top or below), and to depress the center button otherwise, working the sequence from left to right. The ninth response triggered the display of a new sequence, etc., until the trial was terminated after 30 s. The next trial began after a rest break of ~0.5 s, for a total of 12 trials. The remaining time on each trial was displayed continuously on the screen. The letter that subjects momentarily processed was framed by a rectangle, which switched to the next letter immediately after the subjects' response.

Subjective workload was assessed by a German translation of the National Aeronautics and Space Administration's Task Load Index (TLX), in which the psychological, physical, and temporal task demand as well as perceived performance, effort, and frustration are each judged on a 20-point Likert scale.

Subjective mood was captured by the German version of the Multidimensional Mood Questionnaire (30). It consists of 24 items, which are judged on a five-point Likert scale and are then converted to the three mood components: good-bad temper (GB), alertness-fatigue (WT), and repose-turmoil (QR).

Procedures. Before data collection began, subjects were familiarized with the setup and practiced the reaction-time, tracking, dual, and attention tasks on land once, in this order (see Table 1). Subsequently, subjects were then tested once on land (condition DRY) and once under water (condition WET), with the order of conditions counterbalanced across subjects from each body-posture group. One-half of the subjects from each group began each condition with the attention task, followed by the reaction-time tasks (order mixed among subjects), then by the tracking task, and then by the dual tasks (order mixed among subjects). The other one-half began with the reaction-time tasks, followed by the tracking task, then by the dual tasks, and then by the attention task. All subjects completed the workload and the mood questionnaire at the end of each condition.

Data analysis. We quantified performance on the reaction-time task as:

- RT: mean RT of error-free responses

Table 1. *Experiment design for each body posture*

SB 1	TS	SA	4RT	4RT-90	4RTtap	Tracking	Tr + 4RT	Tr + 4RT-90	Tr + 4RTtap	Q	***SA***	**4RT**	**4RT-90**	**4RTtap**	**Tracking**	**Tr + 4RT**	**Tr + 4RT-90**	**Tr + 4RTtap**	Q
SB 2	TS	SA	4RT-90	4RTtap	4RT	Tracking	Tr + 4RT-90	Tr + 4RTtap	Tr + 4RT	Q	***SA***	**4RT-90**	**4RTtap**	**4RT**	**Tracking**	**Tr + 4RT-90**	**Tr + 4RTtap**	**Tr + 4RT**	Q
SB 3	TS	SA	4RTtap	4RT	4RT-90	Tracking	Tr + 4RTtap	Tr + 4RT	Tr + 4RT-90	Q	***SA***	**4RTtap**	**4RT**	**4RT-90**	**Tracking**	**Tr + 4RTtap**	**Tr + 4RT**	**Tr + 4RT-90**	Q
SB 4	TS	4RT	4RT-90	4RTtap	Tracking	Tr + 4RT	Tr + 4RT-90	Tr + 4RTtap	*SA*	Q	**4RT**	**4RT-90**	**4RTtap**	**Tracking**	**Tr + 4RT**	**Tr + 4RT-90**	**Tr + 4RTtap**	***SA***	Q
SB 5	TS	4RT-90	4RTtap	4RT	Tracking	Tr + 4RT-90	Tr + 4RTtap	Tr + 4RT	*SA*	Q	**4RT-90**	**4RTtap**	**4RT**	**Tracking**	**Tr + 4RT-90**	**Tr + 4RTtap**	**Tr + 4RT**	***SA***	Q
SB 6	TS	4RTtap	4RT	4RT-90	Tracking	Tr + 4RTtap	Tr + 4RT	Tr + 4RT-90	*SA*	Q	**4RTtap**	**4RT**	**4RT-90**	**Tracking**	**Tr + 4RTtap**	**Tr + 4RT**	**Tr + 4RT-90**	***SA***	Q
SB 7	TS	**SA**	**4RT**	**4RT-90**	**4RTtap**	**Tracking**	**Tr + 4RT**	**Tr + 4RT-90**	**Tr + 4RTtap**	Q	*SA*	4RT	4RT-90	4RTtap	Tracking	Tr + 4RT	Tr + 4RT-90	Tr + 4RTtap	Q
SB 8	TS	**SA**	**4RT-90**	**4RTtap**	**4RT**	**Tracking**	**Tr + 4RT-90**	**Tr + 4RTtap**	**Tr + 4RT**	Q	*SA*	4RT-90	4RTtap	4RT	Tracking	Tr + 4RT-90	Tr + 4RTtap	Tr + 4RT	Q
SB 9	TS	**SA**	**4RTtap**	**4RT**	**4RT-90**	**Tracking**	**Tr + 4RTtap**	**Tr + 4RT**	**Tr + 4RT-90**	Q	*SA*	4RTtap	4RT	4RT-90	Tracking	Tr + 4RTtap	Tr + 4RT	Tr + 4RT-90	Q
SB 10	TS	**4RT**	**4RT-90**	**4RTtap**	**Tracking**	**Tr + 4RT**	**Tr + 4RT-90**	**Tr + 4RTtap**	***SA***	Q	4RT	4RT-90	4RTtap	Tracking	Tr + 4RT	Tr + 4RT-90	Tr + 4RTtap	*SA*	Q
SB 11	TS	**4RT-90**	**4RTtap**	**4RT**	**Tracking**	**Tr + 4RT-90**	**Tr + 4RTtap**	**Tr + 4RT**	***SA***	Q	4RT-90	4RTtap	4RT	Tracking	Tr + 4RT-90	Tr + 4RTtap	Tr + 4RT	*SA*	Q
SB 12	TS	**4RTtap**	**4RT**	**4RT-90**	**Tracking**	**Tr + 4RTtap**	**Tr + 4RT**	**Tr + 4RT-90**	***SA***	Q	4RTtap	4RT	4RT-90	Tracking	Tr + 4RTtap	Tr + 4RT	Tr + 4RT-90	*SA*	Q

SB, subject; TS, training sequence; SA, sustained attention task; Tr + 4RT, tracking plus targets and buttons spatially congruent; Tr + 4RT-90, tracking plus dual-task buttons rotated by −90° with respect to the targets; Tr + 4RTtap, tracking plus targets and buttons spatially congruent, but subjects depress the button 4 times in a pre-established rhythm; Q, questionnaires. Bold marked tasks represent the condition WET.

- ERR: number of wrong button presses and of RTs outside of the 100- to 1,500-ms range

Tracking performance was determined as:

- RMSE: root mean square tracking error, where "error" is the scalar cursor-target distance excluding the initial 5 s and the final 0.5 s of each trial; when losses of control occurred, the longest data segment without a loss was used for analysis
- LOC: the number of losses of control

When the tracking task was performed alone, we also determined two measures that isolate tracking errors due to slowing from those due to an inaccurate spatial path. This was done by cross-correlation analysis, a powerful method for separating time and shape differences (7):

- δ: delay at which the cross-correlation between cursor and target peaked in the longest data segment without LOC
- CC: magnitude of the cross-correlation peak in the longest data segment without LOC

To quantify dual-task performance, we additionally calculated the dual-task costs as:

$$DTC = \text{dual-task score} - \text{single-task score}/\text{single-task score}$$

The DTC scores thus yielded for RT and RMSE were then averaged to obtain overall DTC, an established measure of dual-task demand irrespective of task priority (26).

Sustained attention was quantified as:

- SA#: number of correctly marked − number of incorrectly marked target letters
- SAi: mean temporal interval between successive button presses

Each parameter of the reaction-time tasks was submitted to a 2 (Condition: DRY, WET) × 2 (Regime: single-task, dual-task) × 3 (Task: 4RT, 4RT-90, 4RTtap) ANOVA with repeated measures on all factors. Each tracking parameter was submitted to a 2 (Condition: DRY, WET) × 4 (Task: tracking and 4RT, tracking and 4RT-90, tracking and 4RTtap, tracking only) ANOVA with repeated measures on all factors. δ, CC, sustained attention SA# and SAi, subjective workload, and the mood components GB, WT, and QR in DRY and WET were compared with paired-samples *t*-tests.

To analyze the influence of body posture on the data in WET, we calculated the differences between WET and DRY for each subject and parameter and submitted the outcome to ANOVAs with the grouping factor Posture and repeated measures on Regime and Task (reaction-time tasks), on Task (tracking task), or without repeated measures (remaining tasks).

RESULTS

Fig. 2 shows subjects' performance in the three reaction-time tasks, separately for DRY and WET, under the single and the dual regime. Fig. 2*A* depicts RT and illustrates that this performance measure differed among tasks, was generally higher under the dual than under the single regime (except for 4RT-90), and was higher in WET than in DRY. These observations were confirmed by ANOVA, which yielded significant effects of Condition [F(1,34) = 68.90; $P < 0.001$], Regime [F(1,34) = 4.97; $P < 0.001$], Task [F(2,68) = 46.87; $P < 0.001$], and Regime·Task [F(2,68) = 26.67; $P < 0.001$]. Post hoc decomposition of the latter effect with Fishers protected least significant differences test confirmed the significance of the regime for 4RT and 4RTtap ($P < 0.05$) but not for 4RT-90.

Fig. 2*B* shows that findings for ERR were, by and large, similar to those for RT. ANOVA confirmed a significant effect of Condition [F(1,36) = 19.24; $P < 0.001$], Task [F(2,22) = 65.90; $P < 0.001$], and Condition·Regime·Task [F(2,72) = 3.96; $P < 0.05$]. Post hoc decomposition of the latter effect confirmed that all tasks except 4RT in single differed between WET and DRY ($P < 0.01$).

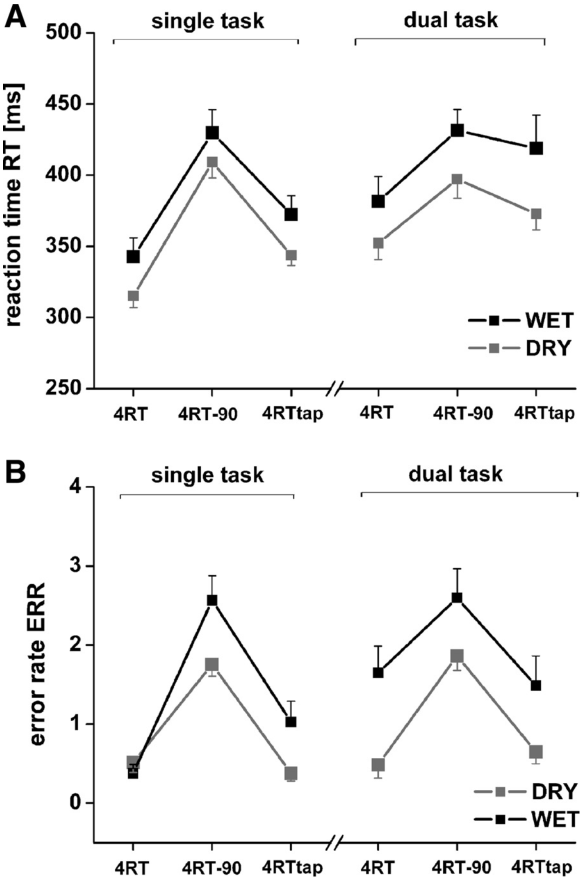

Fig. 2. *A*: release time (RT) in the different reaction-time tasks under the dual- and the single-task regime in conditions WET and in DRY. *B*: error rate (ERR) under the dual- and the single-task regime in WET and in DRY. Note the similarity to *A*. Symbols represent across-subject means and bars SEs. 4RT, targets and buttons spatially congruent; 4RT-90, buttons rotated by −90° with respect to the targets; 4RTtap, targets and buttons spatially congruent, but subjects depress the button 4 times in a pre-established rhythm.

The RT tasks were administered in counterbalanced order to control for serial-order effects such as fatigue and practice. We checked for the existence of such effects in task 4RT by two analyses. The first compared the reaction times of subjects receiving 4RT as the first, as the second, or as the third among the three RT tests in condition DRY: one-way ANOVA yielded no significance for the between-factor order [$F(2,8) = 0.06$; $P > 0.05$]. The second analysis compared the reaction times of subjects receiving 4RT in DRY before WET with those receiving it in DRY after WET: ANOVA was again nonsignificant [$F(1,10) = 2.08$; $P > 0.05$]. We thus have no evidence for serial-order effects.

As Fig. 3*A* illustrates that RMSE was higher in WET than in DRY and higher under the dual than under the single regime. ANOVA confirmed a significant effect for Condition [$F(1,47) = 38.70$; $P < 0.001$] and Task [$F(3,141) = 37.44$; $P < 0.001$]. Fig. 3*B* shows a comparable pattern of findings for LOC, and ANOVA of this parameter yielded a significant effect for Condition [$F(1,47) = 13.54$; $P < 0.001$], Task [$F(3,141) = 12.18$; $P < 0.001$], and Condition·Task [$F(3,141) = 3.08$; $P < 0.05$]. Post hoc analysis of the latter effect confirmed that tracking differed between WET and DRY under the dual (all $P < 0.01$) but not under the single ($P > 0.05$) regime.

The delay in single-task tracking, δ, was larger in WET than in DRY [272.94 ± 54.94 ms vs. 250.40 ± 62.20 ms; $t(47) = 2.07$; $P < 0.05$], but the difference was smaller than it was for single-task reactions [22.54 ± 7.26 ms vs. 40.58 ± 9.58 ms, $t(34) = 7.85$; $P < 0.001$]. The correlation peak, CC, was also larger in WET than in DRY [0.85 ± 0.06 vs. 0.81 ± 0.05; $t(47) = 4.21$; $P < 0.001$]. Thus subjects tracked more accurately in water than on land but with a longer delay.

ANOVA of overall DTC yielded a significant effect only for Task [$F(2,98) = 26.42$; $P < 0.001$] but not for Condition or Task·Condition (all $P > 0.05$).

The attention scores of one subject who did not comply with our instructions were excluded from analysis. The remaining data showed a lower SA# [$t(46) = 4.88$, $P < 0.001$] and a higher SAi [$t(46) = 3.00$, $P < 0.01$] in WET than in DRY, as illustrated in Fig. 4. Thus sustained attention was poorer during immersion than on land.

All six subjective-workload scales and two of the three mood scales did not differ between WET and DRY in *t*-tests (all $P > 0.05$); only the mood scale QR was significantly higher in WET [$t(46) = 2.46$, $P < 0.05$]; i.e., subjects felt more reposed under water than on land.

The differences between WET and DRY regarding RT, ERR, RMSE, LOC SA#, SAi, all workload, and all mood

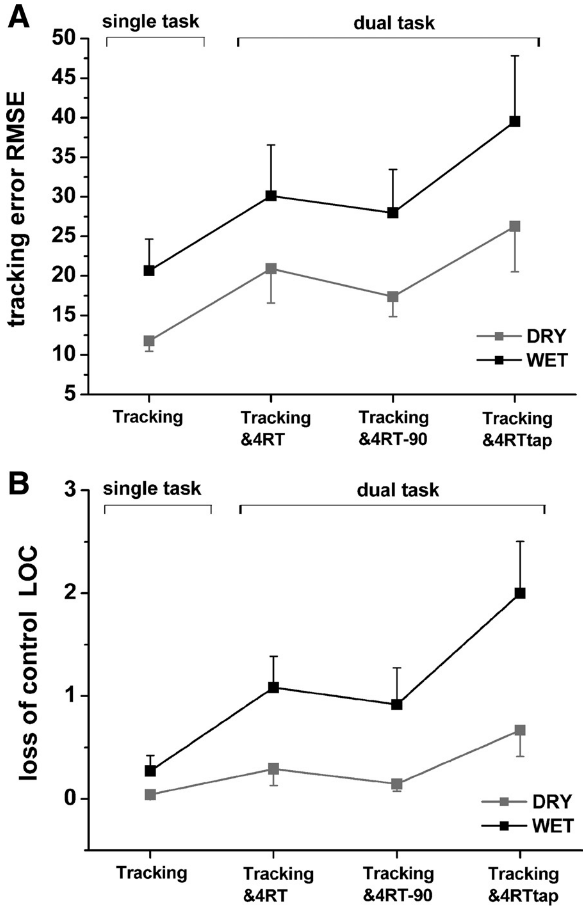

Fig. 3. *A*: root mean square tracking error (RMSE) under the dual- and the single-task regime in WET and in DRY. *B*: losses of control (LOC) under the dual- and the single-task regime in WET and in DRY. Note the similarity to *A*. Symbols represent across-subject means and bars SEs.

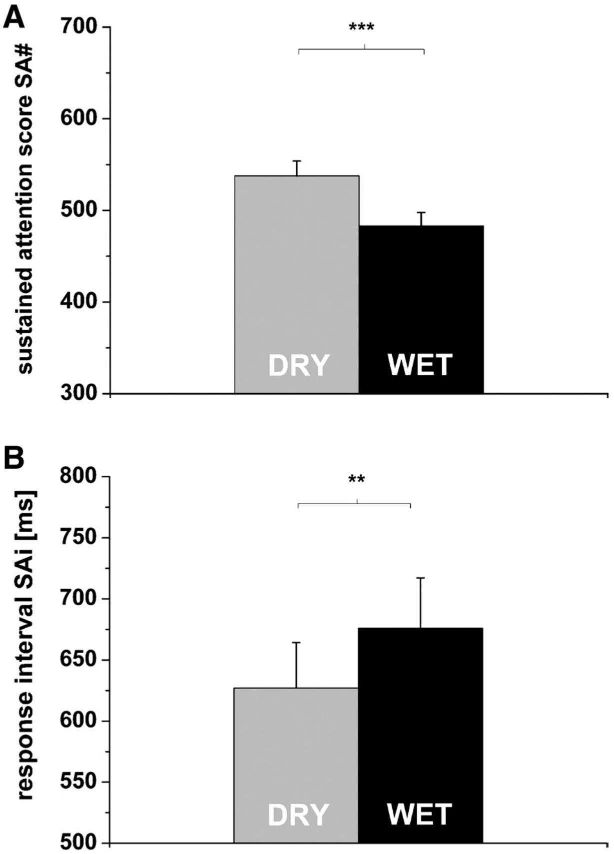

Fig. 4. Sustained-attention scores. *A*: number of correctly marked − number of incorrectly marked target letters (SA#); *B*: mean temporal interval between successive button presses (SAi) in WET and in DRY. Note that attention was poorer during water immersion than on land. Symbols represent across-subject means and bars SEs. $**P < 0.01$; $***P < 0.001$.

scales yielded no significant ANOVA effects of Posture (all $P > 0.05$).

Additional analyses evaluated whether the following differences between WET and DRY were correlated on a subject-to-subject basis: RTs in 4RT, delay in the tracking task, and intervals in the attention task. The correlation between RT differences and delay differences was r = 0.04, that between RT differences and interval differences was r = 0.00, and that between delay differences and interval differences was r = −0.16. None of these correlations was significant (all $P > 0.05$); i.e., we found no evidence that subjects who were more susceptible to immersion on one of the three tasks were also more susceptible to immersion on the other tasks.

DISCUSSION

The present study addresses the apparent discrepancy between experimental findings that suggest intact cognition during shallow-water immersion (16, 23) and experienced divers' introspective observations of moderate cognitive degradation. Specifically, we hypothesized that cognitive deficits might emerge when performance-related cognitive tasks are used rather than the abstract tasks reported in literature.

To avoid the confounding effects of water's viscosity on motor performance, isometric performance was assessed. We found that subjects' reactions slowed down, and their error rate increased under water; both effects of immersion were comparable in a task requiring decisionmaking (4RT), a task additionally requiring visuospatial transformations (4RT-90), and a task additionally requiring preprogramming (4RTtap). We therefore yielded robust evidence that decisionmaking is degraded in shallow-water immersion but cannot confirm an additional degradation of visuospatial and programming skills. It is interesting to note that reactions in 4RT did not slow down in an earlier study where the same equipment was used, but the head was only 20 cm below water level (12): in that study, mean reaction time increased under water by only 4 ms (from 343 to 347 ms), which was not significant, whereas in the present work, it increased by 37 ms (from 332 to 369 ms)[1]. From this, we conclude that response slowing in the present study was not due to effects of water immersion per se, such as changed visibility, discomfort of wearing a mask and a regulator, or anxiety in an unfamiliar scenario. It rather appears that slowing is due to phenomena that are negligible at 20 cm depth but are substantial at 5 m depth.

Response slowing under water was not limited to our discrete reaction-time tasks but also emerged in our continuous isometric tracking task, as an increase of δ. This increase could reflect a degradation of decisionmaking as well, since tracking tasks include ongoing decisions about response amplitude and direction (4, 10, 15, 20). However, the lack of a significant correlation between δ and RT argues against such a causal link.

The immersion-related decrements of performance in the reaction-time and tracking tasks are probably not related to a higher cognitive workload under water, since neither introspective (TLX) nor performance-related (DTC) workload measures were higher during immersion. Interestingly, earlier studies found no increase of the workload as well when isometric responses were executed in hypergravity (10, 14), but a robust increase was observed when actual movements were executed in short-term (4) and long-term weightlessness (7) or under water (29, 31). This pattern of findings could indicate that in unusual gravitational environments, the workload increases for movements but not for isometric responses. Similarly, aiming errors in unusual gravitational environments also increase for movements but not for isometric responses (5, 6, 14). It therefore appears that isometric responses are sensitive to influences that play a minor role for movements—a view that deserves further experimental scrutiny.

We can discount not only workload but also anxiety and subjective stress level as an explanation for the immersion-related decrements in the present study: if anything, subjects felt more relaxed rather than tense under water (QR scale). This is in accordance with earlier work, which reported an increase of anxiety at 30 m but no increase of anxiety and stress hormone levels at 3–6 m depth (13, 23), possibly because captivating tasks can draw attention away from a potential threat (28). Likewise, we found no evidence for an explanatory role of sustained attention: although attention decreased under water, as had been hypothesized by others (3), the decrease was not correlated with the performance decrements in the reaction-time and tracking tasks. Finally, postural disorientation can also be discounted as an explanation, since the observed

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[1] Intraindividual differences between WET and DRY were significantly larger at 5 m depth than at 20 cm depth [F(1,49) = 8.12; $P < 0.01$].

decrements were comparable under all four postures tested: unusual body postures impair spatial orientation on land and under water (19), but we found no evidence that they also degrade manual performance in our tasks. This is relevant for under-water training of divers and astronauts, where the specific postures evaluated in the present study are routinely used (8).

Summing up, we found that immersing a subject's head ~5 m below water level had three uncorrelated effects on the speed of isometric responses: increases of choice reaction time, of the tracking delay, and of the decision intervals in a sustained-attention task. These decrements cannot be attributed to the fact that the higher ambient pressure under water led to mild hyperoxia, since hyperoxia is known to decrease rather than increase reaction times (27). More likely, candidates for the observed decrements could be other effects of higher ambient pressure, such as tactile stimulation and cardiovascular changes, which both might influence cognitive processing.

In any case, our findings support the introspective reports of expert ESA divers about cognitive degradation in shallow water (see Introduction) and suggest that this degradation might be more pronounced in performance-related cognitive tasks rather than in the abstract tasks used in literature. It is interesting to note that professional ESA divers were aware of this degradation, whereas the less-experienced divers from our main study did not report a decrease of performance in the TLX questionnaire. It thus appears that cognitive deficits under water are accessible to introspection only after a substantial level of expertise has been reached. This could be relevant when planning under-water activities for divers early in their careers.

Another issue of practical relevance should be considered as well. We have used isometric tasks to deconfound cognitive deficits from the effects of water's viscosity, whereas the actual duties of divers are mainly nonisometric. Real-life performance of divers is therefore affected not only by changed cognition, as documented in our study, but also by changed viscosity.

It might seem surprising at first glance that one aspect of subjects' performance actually improved rather than degraded during immersion: after tracking delays were taken into account, subjects' tracking accuracy (CC) was higher under water than on land. We attribute this finding to the fact that immersed subjects produce exaggerated forces: when asked to generate predefined force magnitudes, subjects produce higher forces in water than on land (12). When such an exaggeration occurs in an isometric tracking task, it effectively increases the gain of a feedback control system. According to system theory, a moderate gain increase can indeed enhance the performance of a controller, whereas a large gain increase will destabilize it (25). It therefore is conceivable that the observed increase of CC under water is related to the production of exaggerated forces.

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DISCLOSURES

Responsibility for the contents rests with the authors. No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: M.D. and O.B. conception and design of research; M.D. and B.S. performed experiments; M.D., O.B., and B.S. analyzed data; M.D. and O.B. interpreted results of experiments; M.D. and B.S. prepared figures; M.D. drafted manuscript; M.D., O.B., and B.S. edited and revised manuscript; O.B. approved final version of manuscript.

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