Comparing the effects of space flight and water immersion on sensorimotor performance

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Abstract
Several studies documented the detrimental effects of microgravity during spaceflight on human motor control (e.g., during aiming tasks). In addition to parabolic flight, water immersion has been used for simulating microgravity effects on earth. Until now, however, the validity of partial or full water immersion setups as test environments to explore effects on sensorimotor performance has not been tested. In the present paper, the results of three empirical studies were compared using the identical aiming task paradigm during forearm water immersion (N = 19), full body water immersion (N = 22), and during spaceflight (N = 3 astronauts). In line with prior research, slower aiming motion profiles were found during spaceflight (2 weeks in space) compared to the terrestrial experiments. Astronauts required substantially more time to approach target areas and for matching the targets precisely in space. Average motion speed and speed variance decreased significantly. Intriguingly, the same overall effect pattern was evident in both partial and full water immersion, although the effect sizes tended to be smaller. Altogether, results indicate that water immersion is a valid form of weightlessness simulation. However, effects solely present during spaceflight (such as vestibular dysfunction) additionally contribute to performance losses.

Introduction
Until today, the human capabilities and skills are crucial and indispensable for the success of many space missions. Onboard the ISS, astronauts perform challenging tasks such as manual docking of spacecraft, or control of complex robotic systems including the Canadarm 2. Candidates undergo an extremely strict selection process, and are intensively prepared for reliable performance, even under the adverse conditions of space flight. In Earth orbit, the effect of the gravitational force no longer acts on the human body, as a centrifugal force is generated by the orbiting spacecraft leading to a state of microgravity. As one of the most demanding aspects of space flight, human physiology (including the vestibular, cardiovascular, musculoskeletal, and sensorimotor systems) has to adapt to the novel condition of weightlessness which usually takes up to six weeks (Kanas & Manzey, 2008). Astronauts therefore receive extensive trainings during parabolic flights or underwater exercises to prepare for sensorimotor tasks during space flight. These environments, simulating the conditions of space flight, are not only important for
astronaut training but also for scientific research on sensorimotor performance in weightlessness. During parabolic flight, the aircraft is in free fall condition for 20-25s per parabola, causing short-term weightlessness. While under such conditions, space flight conditions can be achieved. Experiments are interrupted during each of the 30-60 parabolas by hypergravity (1.8g) and 1g episodes. Some subjects experience space motion sickness. In research on sensorimotor performance, water immersion studies have been conducted to simulate weightlessness by neutral buoyancy of the human body. Some key advantages include longer experimental periods, larger sample sizes, a higher control of experimental conditions and lower costs. However, the conditions substantially deviate from space flight conditions: 1) the gravitational force is unchanged (i.e., the vestibular system is not affected); 2) increased ambient pressure (e.g., 1.6 bar in 6m depth) leads to cognitive impairment in depths greater than 6m (e.g., Hancock & Milner, 1982); and 3) body motions are damped due to the dynamic viscosity of water.

In the present paper, the validity of water immersion studies for simulating the effects of microgravity on the human sensorimotor system is explored. There is only anecdotal evidence in prior research on the effects of water immersion vs. microgravity. Wang and colleagues (2015) compared general wrist and trunk activities in full water immersion and parabolic flight and reported divergent activity patterns. Whiteside (1960) investigated the sensorimotor performance during an arm pointing task during in water immersion (up to the neck) vs. parabolic flight and reported different results for the two setups - based on data from one subject. In a prior study of the authors (Weber et al., 2016), the effects of full water immersion and space flight were investigated with a zero-order manual pursuit tracking task and documented similar degradations of tracking accuracy. Yet, the experimental setups were not identical (simulation vs. real telerobotic task) and only one astronaut participated in the space experiment.

In the current series of studies, the impact of weightlessness during space flight, partial water immersion, and full body water immersion are compared using the same sensorimotor task. For the current experiments, an aiming task paradigm was chosen, as sensorimotor degradation for rapid, aimed motions has been reliably found in several empirical studies. Using a paper-and-pencil aiming task, Ross (1991) found at least a trend for longer movement times and significantly higher positional error during parabolic flight compared to 1g. Bock et al. (1992) also documented that subjects consistently overshot targets when performing aimed arm movements during parabolic flight. Crevecoeur et al. (2010) found that compared to normal gravity, motions slowed down during parabolic flight with lower peak velocities and higher movement durations during arm movements along the sagittal plane while holding a manipulandum. In the experiment of Newman and Lathan (1999), aiming performance was explored during an 8-day space mission with a joystick and a trackball as input devices. Compared to terrestrial performance, aiming times increased for both devices in microgravity. Results from three cosmonauts, performing pointing arm movements after 10, 140 and 172 days in space also revealed higher motion times, lower peak velocities and accelerations in all phases of the mission compared to the 1g baseline as reported by Berger et al. (1997). Similar kinematic changes during spaceflight (4-18 days in space) have been
documented by Sangals and his colleagues (1999) during a joystick controlled aiming task.

There have been several explanatory approaches for the general slowing of aimed movements in microgravity: 1) a distortion of human proprioception due to the reduced muscle resting tone (no anti-gravity stabilization is required) and hence changed muscle spindle activity (Lackner & DiZio, 2000), 2) an underestimation of limb mass due to the absence of weight (but not mass), see Bock et al. 1996, and 3) inadequate internal movement models (e.g., Crevecoeur et al., 2010).

Theoretically, all of the described mechanisms should be active during water immersion. The buoyant force counterbalances the gravitational force reducing the limb weight – in case of perfect balance – to zero. If the main mechanism behind the degradation of aiming performance is solely due to the weight change of the human limbs, it should also occur during partial immersion, with the respective limbs immersed in water. When controlling a hand-held joystick, for instance, multi-joint interactions involving the trunk, shoulder, upper and lower arm as well as the wrist occur. Berger et al. (1997) hypothesized that the slowing effect may be due to the attempt to reduce reaction forces on the trunk, which is difficult to stabilize in weightlessness. Provided that multi-joint and multi-limb destabilization additionally contributes to the reported overall effect, larger performance decreases should be observed during full body immersion compared to partial immersion. Researchers also suggested that the impairment of the vestibular system could play a crucial role for sensorimotor degradation in space (e.g., Mierau et al., 2008). Then, additional performance losses should be evident during space flight compared to water immersion. These assumptions are tested in a forearm vs. full body water immersion vs. space experiment with the same aiming task paradigm.

Methods

Study 1: Forearm water immersion

Sample. In the first study, $N = 19$ naïve subjects (4 females, 15 males; 1 left-, 18 right-handers) with an average age of $M = 23.1$ (S.D. = 1.16) years participated.

Apparatus. An underwater qualified joystick (2 axes, max. workspace of $\pm 20^\circ$ each axis) with a padded armrest and an elbow strap was positioned in a 50x70 cm basin (see Figure 1). For all of the following studies, all GUI positions could be reached with max. deflections of $\pm 8$ degrees on both axes (resulting in 2 cm motions at the upper joystick end). Thus, anterior/posterior motions could be performed without any (bio-)mechanical restrictions (wrist deflection, elbow motion on armrest). Please note that the hydrodynamic drag is about 15.8 g during aiming motions in the transversal plane (estimated with a $C_D A$ value of 0.36, see Goldstein, 1969, and an average arm speed of 3 cm/ sec, 6 cm/sec at the hand and 0 at the elbow). The elbow strap was designed and attached in a way that allowed unrestricted movement, but also guaranteed a similar arm position for all subjects. The software ran on a real-time PC with a sampling rate of 50 Hz for data recording. The experimental GUI had the size of 20.6 x 17.7 cm for all experiments, displayed here on a 17” LCD monitor.
Experimental task and design. On the experimental screen, crosshairs with black lines were shown on a grey background. Subjects had to move the circular cursor to the starting point at the centre of the crosshairs. Upon reaching the centre, the starting position had to be held for 2 sec, until the aiming task was started. There were four different target ring positions at the intersection points between the black circle and the vertical and horizontal axes (see Figure 1). The centre of the ring had to be matched as quickly as possible and held for 0.5 sec. Then, subjects had to move back to the start position, whereby the next aiming task was started. The order of the four target positions was randomly chosen. Each subject performed the experiment in filled (22°C water temperature) vs. empty basin, while the order of both conditions was counterbalanced across subjects.

Procedure. Subjects were seated at the water basin with a 70 cm distance to the monitor, positioned their right arm on the joystick armrest, attached the elbow strap and grasped the joystick. Subjects were instructed about the experimental task and procedure online. In the “Water” condition the complete joystick and the subjects’ right forearms were fully immersed in the water. In the “Dry” condition the same setup was used in the empty basin. The two conditions were performed on different days, with a maximum interval of 8 days between both sessions. In each session, subjects performed a training trial with four aiming tasks prior to the main experiment. Subjects wore ear protectors to avoid any acoustical disturbances during the experiment. After completing an experimental condition, participants rated the physical effort during the experimental task (“How physically demanding was the last task?”; 20-point Likert scale ranging from “very low” (1) to “very high” (20), adapted from the NASA-TLX questionnaire; Hart & Staveland, 1988).

Study 2: Full body water immersion

Sample. N = 22 subjects, naïve to the experiment (3 females, 19 males; 2 left-, 19 right-handers; M = 27.8 (S.D. = 8.0) years of age) participated in the following study. All of them had at least basic diving experience.

Apparatus. The same underwater joystick as in Study 1 was used for this experiment. The joystick and a water-proof 15” LCD monitor (70 cm distance to subjects’ head) were installed in an aluminium frame (see Figure 2). The experiment was conducted in an upright position and body posture was stabilized by a foot strap.
and an additional holding grip for the left hand. In the underwater condition, the frame was set on the bottom of the 5 m deep pool. The average water temperature was 27° C. Oxygen was provided via a hose connected to a compressed air bottle on deck, i.e., divers did not have to wear a SCUBA jacket during the experiments.

Figure 2. Full water immersion setup.

Experimental task and design. The same experimental task and GUI as in Study 1 was used for Study 2. For the underwater condition, however, the window size was scaled down by 1/3 due to the refractive index (1.33) of the diving mask, leading to a magnification of object sizes. Following the same rationale as Study 1, subjects had to complete a “Dry” and a “Water” condition on different days (max. interval of 8 days), with both conditions being counterbalanced across individuals.

Procedure. In general, the same procedure was realized as in Study 1. In the “Dry” condition, the frame was located on deck and subjects wore ear protectors. Before starting with the underwater sessions, each subject put on a 7 mm short sleeves neoprene suit to avoid hypothermia, a conventional diving mask (prepared with anti-fog spray) and a belt with individually adjusted diving weights to achieve neutral buoyancy.

Study 3: Space flight

Sample. The subjects were three male cosmonauts (42, 45, and 53 yrs.; two with space mission experience).
Apparatus. A space qualified joystick (2 axes, max. workspace $\pm 20^\circ$, 100 Hz sampling rate) was installed onboard the Russian Zvezda service module of the ISS (see Figure 3). The positional resolution of the ISS joystick was higher compared to the underwater joystick, i.e., more fine-grained motions were recorded.

The body stabilization was similar as in Study 2: foot straps on the module “bottom” and an additional grip for the left hand. The experimental GUI window was displayed on the 15.4” TFT display of the laptop.

Figure 3. DLR space qualified joystick and experimental setup onboard the ISS.

Experimental design and procedure

All of the three cosmonauts performed the same experiments as in Study 1 and 2 during a pre-mission training session three months before their mission launch, onboard the ISS (exactly after 2 weeks in space), and a post-mission session, two weeks after completing their half-year space missions. The same procedure (instruction, experimental workflow, and questionnaire) as in Study 1 and 2 was carried out.

Results

The complete aiming motion was split up into two functionally meaningful task segments for a more detailed analysis: a gross motion part and a fine motion part. We recorded the gross motion part from initial motion onset (> 20 pixels (px) distance from start), from experiment start until reaching the target zone. The gross motion part was deemed completed after an interpenetration of 20 px into the target ring. Subsequently, slower and more finely graded motions were performed until the target position was precisely matched with a threshold of 3 px.

For all subtasks the required times were recorded. Additionally, kinematic parameters, i.e., the mean motion speed and the standard deviation of motion speed, were computed for the gross motion part, since effects of water immersion or microgravity should be most evident in the gross aiming motion. For Study 2 the data from one subject was omitted in the subsequent analyses due to the occurrence of several interruptions during the underwater session (problems with the diving mask).
The following statistics were calculated for each measure: arithmetic mean, standard deviation (in parentheses), p-value of the paired samples t-test, percentage change, and effect size (Hedges’ g).

Table 1. Performance measurements for Studies 1-3

<table>
<thead>
<tr>
<th>Study/Measure</th>
<th>Dry/1G</th>
<th>Water/µG</th>
<th>Sign. (t-test)</th>
<th>Rel. Change/Effect Size g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm Water Immersion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross Motion Time [s]</td>
<td>0.351 (0.091)</td>
<td>0.482 (0.210)</td>
<td>( p &lt; .01 )</td>
<td>+37.3%/0.79</td>
</tr>
<tr>
<td>Fine Motion Time [s]</td>
<td>1.772 (0.317)</td>
<td>1.847 (0.361)</td>
<td>ns.</td>
<td>+4.2%/0.22</td>
</tr>
<tr>
<td>Gross Motion Speed [px/s]</td>
<td>844.2 (171.5)</td>
<td>706.9 (209.5)</td>
<td>( p &lt; .01 )</td>
<td>-16.3%/0.70</td>
</tr>
<tr>
<td>Max Gross M. Speed [px/s]</td>
<td>1782.2 (685.0)</td>
<td>1408.2 (517.5)</td>
<td>( p &lt; .01 )</td>
<td>-21.0%/0.60</td>
</tr>
<tr>
<td>SD Gross M. Speed [px/s]</td>
<td>568.7 (190.6)</td>
<td>432.9 (229.5)</td>
<td>( p &lt; .01 )</td>
<td>-23.9%/0.63</td>
</tr>
<tr>
<td>Physical Demand [1-20]</td>
<td>3.684 (2.110)</td>
<td>3.474 (1.926)</td>
<td>ns.</td>
<td>-0.06%/0.10</td>
</tr>
<tr>
<td>Full Body Water Immersion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross Motion Time [s]</td>
<td>0.361 (0.165)</td>
<td>0.442 (0.156)</td>
<td>( p &lt; .05 )</td>
<td>+22.4%/0.49</td>
</tr>
<tr>
<td>Fine Motion Time [s]</td>
<td>1.675 (0.499)</td>
<td>2.223 (0.688)</td>
<td>( p &lt; .01 )</td>
<td>+32.7%/0.89</td>
</tr>
<tr>
<td>Gross Motion Speed [px/s]</td>
<td>747.1 (225.6)</td>
<td>636.5 (164.3)</td>
<td>( p &lt; .05 )</td>
<td>-14.8%/0.55</td>
</tr>
<tr>
<td>Max Gross M. Speed [px/s]</td>
<td>1762.6 (562.6)</td>
<td>1510.3 (502.8)</td>
<td>( p = .06 )</td>
<td>-16.7%/0.46</td>
</tr>
<tr>
<td>SD Gross M. Speed [px/s]</td>
<td>591.4 (221.9)</td>
<td>407.0 (193.6)</td>
<td>( p &lt; .10 )</td>
<td>-16.6%/0.40</td>
</tr>
<tr>
<td>Physical Demand [1-20]</td>
<td>3.833 (3.148)</td>
<td>4.167 (2.915)</td>
<td>ns.</td>
<td>+8.7%/0.11</td>
</tr>
<tr>
<td>Space Flight/ Microgravity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross Motion Time [s]</td>
<td>0.308 (0.057)</td>
<td>0.432 (0.152)</td>
<td>--</td>
<td>+40.3%/0.86</td>
</tr>
<tr>
<td>Fine Motion Time [s]</td>
<td>2.359 (0.213)</td>
<td>3.017 (0.662)</td>
<td>--</td>
<td>+27.9%/1.07</td>
</tr>
<tr>
<td>Gross Motion Speed [px/s]</td>
<td>746.7 (93.0)</td>
<td>632.6 (106.7)</td>
<td>--</td>
<td>-15.3%/0.91</td>
</tr>
<tr>
<td>Max Gross M. Speed [px/s]</td>
<td>2035.0 (520.2)</td>
<td>1453.5 (232.7)</td>
<td>--</td>
<td>-28.6%/1.15</td>
</tr>
<tr>
<td>SD Gross M. Speed [px/s]</td>
<td>667.1 (174.6)</td>
<td>470.8 (116.9)</td>
<td>--</td>
<td>-29.4%/1.06</td>
</tr>
<tr>
<td>Physical Demand [1-20]</td>
<td>4.0 (1.323)</td>
<td>9.0 (3.464)</td>
<td>--</td>
<td>+125%/1.53</td>
</tr>
</tbody>
</table>

Comparing the performance measures in the “Dry”/“1g” conditions across the three studies revealed no substantial differences, except for the fine motion times in Studies 1 and 2 vs. 3. The higher baseline level for the space flight experiment can be explained by the higher positional accuracy of the space joystick, making it more difficult not to exceed the 3 px threshold.

The gross motion times in all of the three studies were significantly increased in the “Water” or “Microgravity (µG)” conditions compared to the “Dry” or “1g” conditions. Large effect sizes were obtained for partial immersion (\( g = .79 \)) and the space study (\( g = .86 \)), while the corresponding effect size in the full immersion study only reached a moderate level (\( g = .49 \)). Regarding the fine motion times, similar significant increases due to water immersion or microgravity were found in the full immersion study (\( g = .89 \)) and the space study (\( g = 1.07 \)), whereas no significant effect (and only a small effect size of \( g = .22 \)) was evident in the partial immersion study.

A highly consistent result pattern was found when analysing the gross motion speed, which decreased significantly in all studies, with moderate effect sizes in the partial and full immersion study (\( g = .70 \) and \( g = .55 \)) and a large effect size in the space study (\( g = .91 \)). Consistently, the maximum speeds decreased in all studies with
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moderate effects during water immersion ($g = .60$ and $g = .46$), as well as a large effect in the space study ($g = 1.15$). Please note, however, that the conventional level of significance was not reached in the full immersion study ($p = .06$). Consistently, the standard deviation of speed decreased in all studies. Results yielded significantly lower values and a moderate effect size for partial immersion ($g = .63$), and a large effect for the space study ($g = 1.06$). Again, no significant effect was observed for the full immersion study, where only a small effect size was found ($p < .10; g = .40$).

Finally, the subjective rating on physical demand during the aiming tasks was explored. Here, we found no effects of water immersion at all, but a large effect size when comparing space and terrestrial conditions ($g = 1.53$).

**Discussion**

In three empirical studies, the effects of weightlessness on aimed arm movements was investigated during forearm water immersion, full body water immersion in 5m depth and during spaceflight after 2 weeks in space.

In all of the three setups, the same result pattern for rapid, gross arm motions is evident: weightlessness caused significantly longer motion times (+22–40%), lower maximum (-17–29%), mean speeds (-15–16%) and speed variance (-17–29%). This overall pattern is consistent with prior research, which demonstrates that sensorimotor control is substantially degraded in weightlessness, resulting in decelerated motion profiles. The magnitude of this effect varies individually, as reported by Bock (1998). Maybe, different individual vulnerability to weightlessness also factor into the smaller effect sizes found in the full body immersion study.

Regarding fine motion, longer times are required in all setups, although large effects are only evident during full immersion (+33%) and space flight (+28%), while only a minimal effect emerges for partial immersion (+4%). Mean motion speed and variance of speed are also reduced for this aiming phase, as indicated by additional analyses. In the target zone, gross arm motion has to be decelerated abruptly and several motion reversals have to be performed until matching the target precisely. A plausible explanation for the above results can be that multi-limb coordination or stabilization play a significant role during these dynamic positional corrections. In the case of full immersion or space flight, the complex coordination of the inertial load and reactive forces of all limbs and joints involved is more difficult and thus the dynamic impulses are reduced.

Interestingly, the weightlessness of the human forearm seems to be sufficient to induce a slowing of gross aiming motion. It could be argued that this effect is a direct result of water viscosity. There are several facts contradicting this assumption: 1) the C$_{OPA}$ values for forearm motions in the sagittal plane (top and bottom aim) should be substantially lower than the corresponding values for arm motions in the transverse plane (left and right aim). However, no significant differences regarding maximum speeds for the both movement planes of the immersed forearm are found, 2) there is no significant correlation ($r = 0.03$) between the subjects’ maximum speed in the “Dry” condition and the decrement of maximum speed in the “Water” condition, 3) the overall result pattern is very similar to the space flight results.
As discussed in the introduction, cognitive impairment may affect performance during full body immersion due to higher ambient pressure (1.5 bar in the present study). Moreover, it has been discussed that a higher cognitive load e.g. due to increased general stress level during a space mission has a detrimental effect on sensorimotor performance (Manzey et al., 2000). In additional analyses, we did not find any significant changes of response times in weightlessness, which would be an indication of reduced cognitive resources.

Comparing the water immersion setups with space flight revealed two main differences: 1) sensorimotor degradation is even more pronounced in space, with large effect sizes for all the performance measures and 2) the subjectively rated physical effort was significantly higher in space compared to the terrestrial sessions. Seemingly, the changed gravitational state further contributes to the degradation motor control. Lackner and DiZio (1992) emphasized that muscle spindle activity is also modulated by vestibular activity. The additional vestibular dysfunction explains the stronger effects during spaceflight and might also be the reason for higher physical efforts astronauts have to expend to stabilize their motions. Other studies investigating force production with an isometric joystick (i.e., the joystick is not deflected) successfully demonstrated that the changes of proprioception due to weightlessness can also be shown during water immersion (exaggerated peak and end forces; Dalecki, 2013). However, the specific effects attributed to vestibular dysfunction (higher initial forces) could not be documented in the underwater condition.

Altogether, promising results could be gathered showing that the general effect direction of weightlessness on sensorimotor performance can be effectively simulated by water immersion. Even for rapid aiming tasks - requiring joystick deflections - the water immersion analogue is able to simulate key aspects of space flight, making it a valuable tool for future research.

References


