Disentangling the enigmatic slowing effect of microgravity on sensorimotor performance

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Abstract

The success of many space missions depends on astronauts' performance. Yet, prior research documented that sensorimotor performance is impaired in microgravity, e.g. aimed arm movements are slowed down and are less accurate. Several explanatory approaches for this phenomenon have been discussed, such as distorted proprioception or stress-related attentional deficits. In the current work, sensorimotor performance was investigated during aimed joystick-controlled motions in a simulation. The task included rapid as well as fine matching motions. Results of two different studies were compared: 1) a study utilising a dual-task paradigm to investigate the impact of attentional distraction (N = 19) and 2) a study investigating the impact of microgravity during spaceflight (N = 3). In both studies, an overall slowing effect was found. However, results diverged when comparing feedforward vs. feedback-controlled parts of aiming. Reduced attentional resources mainly affected feedforward control, which was reflected in significantly longer response times and longer rapid motion times. Microgravity, however, did not affect response times at all, but rapid aiming times as well as fine matching times substantially increased. These findings provide evidence that impaired attention is not the main trigger behind the slowing effect, but rather it is distorted proprioception which impairs feedback controlled motions.

Introduction

Space agencies around the world are planning crewed lunar and Mars missions to be realised within the next decade (International Space Exploration Coordination Group, 2018). Apart from the enormous technological challenges, these human space exploration missions would also critically depend on human capabilities and performance. It has been shown, however, that adaptation to the adverse space environment is challenging - even for astronauts who passed a hard selection and training process before starting their mission. Spaceflight has a substantial impact on human physiology (e.g. cardiovascular, vestibular and sensorimotor systems), sleep and circadian rhythms are disturbed, and psychological stressors such as isolation, confinement, high workload, etc. additionally compromise astronauts' well-being and performance (see Kanas & Manzey, 2008 for an overview).

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Furthermore, many basic functions like spatial orientation, oculomotor control, posture and locomotion (see Lackner & DiZio, 2000) as well as mass discrimination (Ross et al. 1986; Ross and Reschke, 1982) are affected by microgravity. Prior research repeatedly documented that human motor performance is also degraded in microgravity (see Bock, 1998; Lackner & DiZio, 2000). Impairments have been found across different task paradigms like aiming (e.g. Bock et al., 2001), tracking (e.g. Manzey et al., 1993) and force production (e.g. Mierau & Girgenrath, 2010). When performing rapid aiming movements in weightlessness, a general slowing-down effect was found, i.e. peak accelerations decreased and motion times increased accordingly (Berger et al., 1997; Bock et al., 2001; Crevecoeur et al., 2010; Mechtcheriakov et al., 2002; Newman & Lathan, 1999; Ross, 1991; Sangals et al., 1999). Moreover, positional accuracy in tracking tasks decreases (Bock et al., 2003, Manzey et al., 1993, 1995, 2000) and studies on isometric force production reported less accurate force regulation in weightlessness (Mierau, et al., 2008; Mierau & Girgenrath, 2010).

Several explanatory approaches for the substantial deterioration of basic and indispensable sensorimotor skills in microgravity have been proposed. Frequently, researchers explain their findings by disturbed proprioception in altered gravity conditions (e.g. Bock et al., 1992, 1998; Fisk et al., 1993, Manzey et al., 2000). According to this approach, muscle spindle activity which is crucial for proprioception is altered by the weightlessness of the body and limbs (e.g. Lackner & DiZio, 2000). Consequently, the sensorimotor system is in a state of “sensorimotor discordance” (Bock, 1998) and has to adapt to the lack of valid proprioceptive feedback. Corrective motor responses would be delayed due to additional information processing. The general slowing-down effect for aiming tasks and time-delayed correction initiation during tracking (Manzey et al., 2000) support this notion. Moreover, weightlessness effects were stronger in dual-task performance compared to single-task performance in the early mission phase (Manzey et al., 2000) or during parabolic flight (Bock et al., 2003), providing evidence for higher resource demands in the initial phase of adaptation to microgravity.

However, the impaired proprioception approach is not sufficient to explain the performance decrement in the early and late phases of the 20-days mission reported by Manzey and his colleagues (1995, 2000) during tracking tasks. The performance losses in the later phase were explained by prolonged work and the cumulative impact of general stressors of the mission. While higher cognitive functions (memory, reasoning etc.) are seemingly not impaired by spaceflight, attentional selectivity affects performance in weightlessness as revealed in dual-task paradigms (Bock et al., 2003; Fowler et al., 2008; Manzey et al. 1993, 1995).

Still, the specific contributions and relevance of both mechanisms to the overall microgravity effects on sensorimotor performance are difficult to determine and researchers attributed their results either to distorted proprioception (e.g. Bock, 1998), cognitive load (e.g. Fowler, 2008) or both processes (e.g. Manzey, 2000). Most studies investigating the degradation of sensorimotor performance in space utilised aiming (arm movement or device control), arm tracking, or unstable, compensatory tracking (joystick controlled) as experimental paradigms. Like any voluntary motion task, these tasks require feedforward motion planning as well as feedback-controlled motion sequences, while the relative contribution of both control types is contingent on task demands. During rapid, aimed arm movement a major part of the movement has to be planned as a pre-programmed forward model that is corrected and updated by feedback loops integrating afferent information in the course of motion execution. During motor tasks requiring slow and precise closed-loop motions (e.g. tracking) the major part of motion control is based on visual and proprioceptive feedback (Desmurget & Grafton, 2000). Although optimal motion control relies on feedforward as well as feedback processes, they are two distinct mechanisms which are controlled by different brain structures. While cortical structures (e.g. primary motor cortex) have been identified to be mainly responsible for feedforward processes, subcortical structures (e.g. cerebellar regions) are associated with feedback control, as reported by Seidler and colleagues (2004), who analysed fMRI recordings during joystick controlled aiming tasks. In their study, the activation of these brain regions was moderated by task difficulty, i.e. cortical activity was positively correlated with increasing target size and subcortical activity was negatively correlated with target size.

Distinguishing these two basic functions of motor control seems a promising approach to better understand the mechanisms behind sensorimotor performance losses in space. Provided that distorted proprioception is the main trigger of performance decrements, then it is obvious that the feedback-controlled parts of motion should be mainly affected. On the contrary, a potential attentional deficit should mainly interfere with feedforward control. Johansen-Berg and Matthews (2002), for instance, could show that attention distraction (counting back in threes as the secondary task) affects the activity in the motor cortical areas including the primary motor cortex when performing the primary target acquisition task. In another dual-task experiment, Taylor and Thoroughman (2007) also found evidence that corrective movements (i.e. feedback control) were not affected when performing arm reaching tasks with a manipulandum that introduced random perturbations. However, the secondary task (auditory discrimination task) did interfere with adjustments of the feedforward model.

Based on this evidence and these considerations we designed an experimental aiming task, allowing a discrimination of feedforward and feedback controlled motor performance. In the present work, this experimental paradigm is pre-tested under terrestrial conditions to identify the impact of attentional distraction on performance during rapid, open-loop aiming and subsequent slow, terminal corrective adjustments. In a next step, the same aiming task is performed by cosmonauts in terrestrial and mission sessions on-board the ISS (2 weeks in space) to determine the effects of spaceflight.

An overall increase of aiming times is expected when attention is distracted as well as during spaceflight. More specifically, however, it is hypothesised that:

> H1: *Feedforward control is mainly affected by attentional distraction while feedback control is mainly affected by distorted proprioception during spaceflight.*

Thus, performance losses due to attentional deficits should primarily result in increased reaction times and rapid motion times (Fowler et al., 2000, Fowler et al., 2008). Performance losses due to proprioceptive deficits should be evident for fine motion times as reported by Fisk and colleagues (1993).

Methods

Study 1: The Effects of Attentional Distraction

Sample. Nineteen subjects (5 females, 14 males; *M* = 24.6 (2.5) years of age) voluntarily participated in the study after having signed an informed consent document.

Apparatus. Participants were seated at a table, in front of a notebook (Lenovo T61P-6457) with a 15.4” TFT display showing the experimental GUI. The space qualified Joystick “Kontur-2” developed at the German Aerospace Center (Riecke et al., 2016, workspace of ±20° in each axis, angular resolution of $3.18°\cdot 10^{-3}$, see Fig. 1, left), was connected to the computer. For the present experiment, an upward motion scaling of 1:2 was implemented, i.e. the required experimental workspace was fully covered with joystick deflections of ±10° for both axes. Data were recorded with a sampling rate of 100 Hz.

Experimental Tasks.

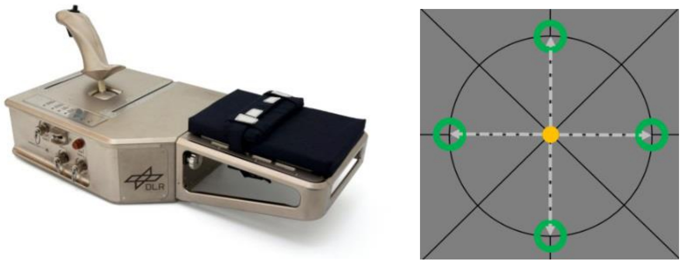

Figure 1. Joystick “Kontur-2” (left); Experimental GUI with cursor at starting position and the four different target positions (right).

Primary Aiming Task: The experimental GUI showed black crosshairs on a grey background (see Fig. 1, right). The aiming trials were started by moving the black cursor exactly to the crosshair’s center. Upon reaching the center, the cursor turned green and a countdown was displayed on the screen. After holding the position for 2s the cursor turned orange and a green target ring was displayed at one of the four different target positions (see Fig. 1, right). The cursor had to be brought to the center of the target ring as quickly as possible and the final position had to be held for 0.5 sec. Subsequently, the next trial was started and subjects moved back to the centre of the crosshairs. Please note that the order of the four target positions was randomly chosen to avoid anticipatory movements.

Secondary Counting Task: During the aiming tasks, subjects had to count forwards in intervals of seven starting with 12 up to 103 and then backwards again (12-19-26-

33-…-103-96-89-82-….12). An acoustic signal (metronome sound) prompted the subjects to speak the next number aloud every 4 seconds.

Experimental Design. A within-subject design was utilised with all subjects completing a single-task condition (aiming task only) and dual-task condition (aiming and counting) while the order of both conditions was counter-balanced across subjects.

Procedure. Chair height was individually adjusted by the participants so that their right arm rested comfortably on the joystick's padded arm support. For reasons of standardisation, subjects also attached a strap around the right elbow, ensuring that arm orientation and position was comparable across participants but still allowing free motion in the required range of motion. Participants read the instructions that were displayed on the monitor. The two experimental conditions (single vs dual-task) were presented in a sequence, separated by a short break of 2–3 min. In each condition, two aiming trials were performed for training, and then the experimental trials were started. After having completed these trials, subjects were asked to rate their perceived workload ("Please rate your overall workload during the last task", adapted from the OWS scale, Vidulich & Tsang, 1987; 20-point bipolar scale ranging from "very low" to "very high").

Study 2: The Effects of Spaceflight

Sample. The subjects were three male cosmonauts (42, 45, and 53 yrs.; two of them with space mission experience).

Apparatus. The same joystick was installed on board of the Russian Zvezda service module of the ISS (see Figure 2). Body stabilisation was realised by rails 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 notebook (same as in Study 1).

Figure 2. Cosmonaut Andrei Borisenko at the experimental workstation on board the ISS.

Experimental Design and Procedure. All of the three cosmonauts performed the same aiming tasks as in Study 1 (without a secondary task) during a pre-mission training session three months before their mission launch, on-board the ISS (exactly two weeks after Soyuz docking) and during a post-mission session, two weeks after having finished their half-year space missions. The procedure (instruction, experimental workflow and questionnaire) was similar to the procedure in Study 1.

Data analysis. Reaction times, rapid motion times and fine motion times were calculated for each aiming trial. Reaction time was defined as the time from task start until exceeding a pre-defined threshold velocity (in contrast to the positional threshold approach the authors utilised in a prior study; Weber et al., 2018). Rapid motion time was the time from exceeding the threshold velocity until the center of the cursor touched the green target ring. Fine motion time was the remaining time until target and cursor centers were precisely matched and constantly held for 0.5 sec. These temporal variables were averaged across all of the four targets. For Study 1 the single and dual-task conditions were compared using paired t-tests. Additionally, the effect sizes were calculated using Hedges' g. In Study 2, only effect sizes were determined due to the small sample size. Results of both terrestrial conditions (pre- and post-mission) were averaged and utilised as a comparison baseline for mission session.

Results

Study 1. Performing paired t-tests on the average reaction times and rapid motion times revealed a significant increase in the dual-task compared to the single task condition (for both conditions, $p < .05$; see Table 1). A large effect was evident for reaction time (g =.82) and a moderate effect for rapid motion time (g =.68). No significant difference was found for fine motion times. Finally, the subjective workload rating was significantly increased in the dual-task condition (p <.001).

The number of counting errors during the secondary task and the reaction as well as rapid motion times were positively correlated ($r_{RT}(19) = .50$; p <.05 and $r_{RMT}(19) =$ .51; p <.05). Seemingly, no task switching occurred, but both primary and secondary task were influenced simultaneously.

Study 2. A quite different result pattern was found in Study 2, comparing terrestrial conditions (1g) and microgravity (µg) conditions during spaceflight. When comparing both conditions, large effect sizes were evident for rapid motion (g =.80) and fine motion times (g =1.08). Regarding workload ratings, a small effect of microgravity (g =.27) was found, i.e. workload increased marginally.

Table 1: Performance Measures (M (SD), paired t-tests and Hedges' g for Study 1 and 2

Study 1 (n =19)		**Terrestrial Dual-Task Experiment**			
Measures		**Single Task**	**Dual Task**	Sign. (t-test)	Effect Size g
Reaction Time	[s]	0.139 (0.064)	0.303 (0.271)	*p* < .05	**0.82**
Rapid Motion Time	[s]	0.545 (0.167)	1.242 (1.419)	*p* < .05	**0.68**
Fine Motion Time	[s]	2.467 (0.969)	2.164 (1.139)	*n.s.*	0.28
Overall Workload	[1-20]	6.3 (4.0)	11.5 (4.1)	*p* < .001	**1.27**
Study 2 (n = 3)		**Space Flight Experiment**			
Measures		**1g**	**µg**		Effect Size g
Reaction Time	[s]	0.220 (0.077)	0.216 (0.010)		0.06
Rapid Motion Time	[s]	0.394 (0.046)	0.503 (0.148)		**0.80**
Fine Motion Time	[s]	2.351 (0.232)	3.020 (0.663)		**1.08**
Overall Workload	[1-20]	4.3 (2.08)	5.0 (2.00)		0.27

Discussion

The slowing of aimed arm movements in microgravity has been repeatedly documented by researchers since the early 1990s. However, this phenomenon remained enigmatic due to the substantially altered working conditions of spaceflight and multiple potential mechanisms triggering such sensorimotor performance losses. In prior research, two explanations for the slowing effect of microgravity have been discussed: distorted proprioception due to the lack of a gravitational force and attentional selectivity due to general mission-related workload. In the current paper, a simple joystick-controlled aiming task was utilised to explore the effects of reduced attentional resources and spaceflight on feedforward and feedback controlled parts of motion.

It was hypothesised that decreased attentional capacity would mainly affect feedforward control and deficient proprioception would mainly affect feedback controlled motions. Indeed, two substantially divergent result patterns are evident for both studies: When performing a concurrent counting task, motion planning and the early feedforward controlled aiming motion are significantly disturbed as reflected by increased reaction and rapid motion times compared to the single-task condition. No significant effect emerges for the feedback-controlled fine motion section. In contrast, the cosmonauts did not show any additional delay of reaction times in microgravity compared to the terrestrial baseline condition, but rapid motion and fine motion time increase. Note that the overall effect pattern is diametrically opposed. Reducing attentional resources has the strongest effect on motion initialisation, but disappears towards the end of motion. Regarding the impact of microgravity, the inverse pattern emerges: the effect increases the more feedback is required for motion plan corrections. Altogether, this confirms the formulated hypothesis and provides evidence that – in this case – a proprioceptive deficit is the main trigger behind the slowing effect of microgravity. The subjective ratings additionally provide further evidence that, in the present study, increased workload is not a plausible explanation for slowed aiming motions in microgravity.

Although a stronger impact of attentional distraction was expected for the rapid motion times, a similar slowing effect occurred during spaceflight. This result might be explained by the fact that the rapid, open-loop arm motion is not exclusively executed on basis of pre-planned forward models, but also integrates feedback during the ongoing motion. In line with this notion, Bock et al. (2001) also reported no effect of microgravity on aimed arm motions in the initial 80ms, but motions increasingly slowed down towards the end positions. Indeed, the minimal delay of proprioceptive feedback loops ranges between 80 and 100ms. Thus, internal feedback loops refine the initial motion plan even during rapid arm motions (Seidler et al., 2004).

Additional analyses of the aiming trajectories recorded in Study 2 also revealed that cosmonauts show very irregular and unstable motion paths when moving their arm in the sagittal plane (i.e. vertical motion axis in the experimental GUI) in microgravity. The occurrence of this direction-specific effect (anisotropy) might also be an indicator of a proprioceptive deficit as documented in studies investigating aiming motions of patients without proprioception caused by large-fiber sensory neuropathy (e.g. Ghez et al., 1990).

One major limitation of the current study is that no dual-task condition was implemented in Study 2, which actually was an integral part of a series of experiments pursuing a different research agenda. Thus, the question how attentional and proprioceptive processes interact during spaceflight cannot be answered with the present work. It is well conceivable, for instance, that a mismatch of internal motion models and afferent information also leads to increased attention demands as reported by Ingram and colleagues (2000).

The comparison of two studies investigating attention distraction and microgravity effects on basic aiming tasks provides evidence that distorted proprioception seems to be the main mechanism underlying the slowing of voluntary aiming motions at least in the early phase of a space mission (two weeks in space). The question still is whether the terrestrial performance can be reached again after having completed the initial adaptation to the space environment. A recent study of the authors (Weber et al., 2019) investigating the effects of spaceflight on performance during a real telerobotic aiming task, provides evidence that performance is degraded even after six weeks of space travel, seemingly due to an altered motion strategy. For human space missions to be successful it is imperative to identify effective measures to attenuate these performance losses, e.g. by providing haptic assistance as part of the human-machine interface, or intention-detection concepts.

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