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The Impact of Altered Gravitation on Performance and Workload of Augmented Reality Hand-Eye-Coordination: Inside vs. Outside of Human Body Frame of Reference

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Abstract

We investigated new interface technologies to ease astronaut′s work under altered gravity. By bridging the gap between the physical reality and digital information, Augmented Reality keeps the focus on the task to fulfill. It is important that the operation of such Augmented Reality supported assistant systems is adequate preserved in weightlessness. By distinguishing the interface alignment to the body and outside of the body, this paper presents a user study conducted to quantify and qualify the impact of altered gravity on sensorimotor hand-eye coordination related to the human body frame of reference. Taking the advantages of parabolic flights, we compared the performance of this alignment methods under normo- and altered gravity. Beside of verified effects of altered gravity on aimed pointing movements, the study showed a higher efficiency and decreased workload for the body aligned condition.

1. Introduction

Astronauts′ performance of demanding skilful tasks to operate the on-board systems on the International Space Station (ISS) implies complex visual-motor tasks under weightlessness. The crew members have to carry out daily numerous maintenance and experimental activities at ISS payloads (e.g., Biolab). The necessary guideline information is obtained from a laptop computer and is crucial for a successful performance. To ease astronauts′ activities, the application of new interface technologies is investigated [SNK*10] [AL12]. Presently we are designing and evaluating a head-mounted Augmented Reality (AR) assistance system for space operations to improve the support for the space crew. The use of AR [Azu97] retains the presence of the physical reality but also can bridge the gap to the common payload procedure guidelines by enhancing appropriate 3D registered digital information in real-time. This could enable an increase of astronaut′s perception and can enhance the quality and reliability of the performed tasks. Because the design of AR interfaces nearly always matches real-world environments, it is important to optimize the interaction technique for the environmental condition of the target task [BKLP07]. Working in space under altered gravity denotes an increased workload of the astronauts′ performance and it is therefore of particular importance to investigate whether visual-motor performance is preserved adequate in weightlessness when operating AR interfaces. Goal-directed movement tasks, such as the selection of an object, are fundamental key factors to interact with our surrounding environment and thus also essential for AR selection to acquire a virtual target for object manipulation [LBGC07] [BVBC04], or to operate ”soft” input devices [BKLP07] [HBW11] [KT02] and system control tasks [YON04]. Several studies [BHMA92] [BFC01] where performed to investigate sensorimotor performance by the control of aimed arm movements under weightlessness. Our research deals with the influence of gravity in aimed pointing movements for AR selection correlated to the location of the interface that are different specified in human′s egocentric body frame of reference. Thereby we distinguish between target′s location coded outside of the frame (stationary on a physical surface) and inside of the frame (relative to limb position). The first experiment was done in May 2012 [MMS12] and found that haptic feedback is required for AR selection under hyper- and microgravity. Because of the low sample size we could

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not show the relevant reference system of human′s body frame.

This paper presents a study conducted to quantify and qualify the impact of altered gravitation on human hand-eye coordination while pointing towards virtual targets attached and displayed in the real world by an optical see-through head-mounted display. In response to visual stimuli we verified the performance and workload of precise object selection in conjunction with target′s location affected by hyper- and microgravity. Table 1 shows the two methods (BA, PA) for target′s location that we have studied. While the inside BA (body aligned) method as handheld interface can be controlled by movements of the head and the hand with the fixed target, the outside PA (physical surface aligned) method can be controlled by head and body movements (to orient towards the target). We hypothesize that aimed pointing movements performed inside human body frame of reference (BA) increases the efficiency and decrease the workload of human hand-eye coordination task under hyper- and microgravity. Compared to our previous study [MMS12], we additionally measured and analyzed the accuracy of the pointing performance and physiological responses as strain indicator. These responses were obtained from the heart rate variability (HRV) as an essential parameter for analysis of the heart function and the activity of the autonomous nervous system (ANS). It is defined as variation and fluctuation of heart rate during a certain period of time. HRV has been applied during previous AR studies for evaluating subjects′ strain [TMS*08] [OSL02] or to measure the presence and immersion in virtual environments [GEL*04] [WDW98]. In the present work we investigated the subjects′ strain index (SI) by HRV. The SI describes the equilibrium within the ANS which consists of the sympathetic (exciting) and the parasympathetic (calming) part. Therefore, it can be applied to measure the physiological and cognitive workload during a defined period of time.

Method	Location	Description
BA	inside	Handheld AR panel that is fixed at subject′s non-dominant hand.
PA	outside	External AR panel that is fixed at a physical surface in front of the subject.

Table 1: *Experiment methods (independent variables) of target′s location related to human′s egocentric frame.*

2. Methodology

To investigate sensorimotor hand-eye coordination under altered gravitational conditions we performed a comparative usability study under parabolic flight conditions in June 2013. Parabolic flights [ESA05] are aircraft maneuvers that provide one period up to 22 seconds reduced gravity or weightlessness surrounded by increased gravity (≈1.5G to 1.8G). We conducted the study during three flight days with 31 parabolas per day. Figure 1 shows the parabolic flight profile that was provided on all flight days. Each parabola (see Fig. 5) takes around three minutes and includes the up- and downwards hypergravity phases (1.8G) and the microgravity phase (0G). The corresponding test series under normogravity were performed one day before flight on ground (1G PRE) and between the parabolas in flight (1G). The experimentation in flight was performed by two subjects. While the subjects completed successively the experiment task, an operator was responsible for the coordination and the data collection unit. Each subject performed the experiment within 14 parabolas. An assistant was responsible for subject′s safety and fixed slightly the subject under microgravity (see Fig. 2). Overall six subjects performed the test series at three flight days. The subjects were precisely informed about the experiment protocol and signed an informed consent form. To avoid motion sickness during the flight, each subject was administrated with Scopolamine.

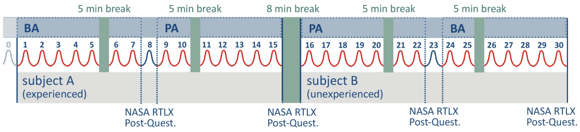

Figure 1: *The flight profile of the 58th PFC.*

Figure 2: *The PA mode under 1.8G and 0G using to a surface installed at the handrail. The subject is fixed by the assistant.*

2.1. Apparatus

The experiment was conducted aboard the NOVESPACE Zero-G Airbus A300. Providing head-mounted AR we used a right-sided monocular optical see-through head mounted display (OST HMD, Shimadzu dataGlass2/a) which has a semi-transparent LCD display with a resolution of 800x600 pixels and a diagonal field of view (FOV) of 30 degrees (see Fig. 3). The HMD was mounted on a bicycle helmet, that allowed a quick change of the HMD setup and was connected to the data processing unit (Lenovo Thinkpad T420s, 2.8 GHz CPU, NVIDIA Quadro NVS 4200M). For optical inside-out marker tracking we equipped the HMD with an optical sensor (Microsoft HD 5000 webcam with 66 degree diagonal FOV). To compute the position of subject′s eye relative to the optical sensor, each subject has performed a self-calibration [KB99] once before experimentation in the aircraft. To realize pointing towards the BA and PA panel we used different physical marker configurations: a single marker attached to the fingertip of the dominate hand and multi-marker configurations for the panels. For the BA method the subject fixed a multi-marker to the non-dominate hand. Setting up the environment for the PA method we designed a physical surface that was installed at the handrail (see Fig. 2) and equipped with a multi-marker configuration. To ensure the correct fitting of the pointer marker, we visualized a virtual hand model and the subject was requested to align his fingertip to the virtual fingertip. The operational software system was written in C++ using Qt for operator′s 2D user interface, ARToolkit [KB99] library for marker tracking and OpenSceneGraph for rendering the virtual content. To measure the physical workload by the heart rate variability, the subject was wearing a wireless eMotion HRV sensor from Mega Electronics. The HRV electrodes were placed under the flight suit (see Fig. 3).

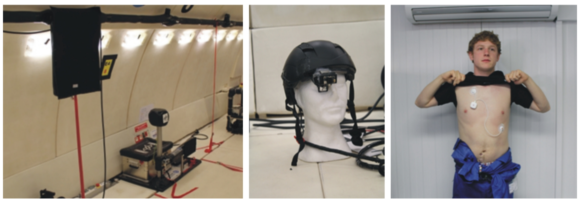

Figure 3: *Apparatus. (LEFT) The experiment setup inside of the Zero-G A300. (MIDDLE) The monocular OST HMD. (RIGHT) Attached HRV sensors.*

2.2. Subjects

The experiment was performed by 6 participants (1 female and 5 male) from 26 to 51 years (average 32.2). Three subjects had experiences in parabolic flights previously and three subjects were novice. All subjects were right-handed. Three subjects had a dominant right eye, while the other three subjects had a dominant left eye. Three subjects had little experience working with AR/VR and three subjects were novices in this field. They came from the fields aerospace, biology and media. All subjects received Scopolamine by injection as anti-motion-sickness medication: 0.4 mg (1 male), 0.5 mg (1 male), 0.7 mg (2 male), 0.8 mg (1 female) and 0.9 mg (1 male).

2.3. Experimentation Task

The design of the task to be performed during aircraft maneuvers required a short, repeatable, but still realistic task. To investigate the performance and workload of controlled AR pointing movements, we implemented a virtual keyboard designed with the common QWERTZ layout. The subject was requested to enter random signaled letters on the keyboard (see Fig. 4). The requested letters were highlighted in green. By hitting a correct key, it was highlighted in red and the next key was highlighted. In case of incorrect key hitting, the false key was highlighted in red, but the requested key was still highlighted in green. We used seven randomized key pools with 25 pre-randomized keys per pool, one pool for one test series.

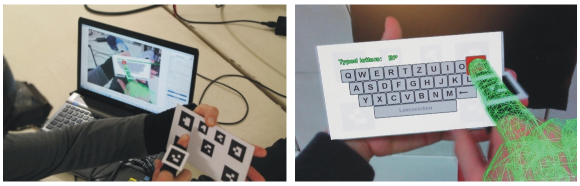

Figure 4: *Experimentation Task of pointing towards an AR keyboard using the BA Method.*

2.4. Experimentation Schedule and Design

The test series was conducted by the subject on ground in the aircraft and in flight (see Fig. 5). For the experimentation in flight we used the upwards hypergravity phase (22 s), the microgravity phase (22 s) and 22 s of the 1G phase. The comparable ground study (1G PRE) was performed in the aircraft one day before. Each test was performed in upright posture. In microgravity the subject came up in upright floating posture. Because three subjects were experienced in parabolic flight, they performed the test series in flight in the first part (see Fig. 1). The unexperienced subjects could spend this inactive time to become familiar with the gravitational condition. By inception the hypergravity and the microgravity level, the operator started the experiment session timer and the first key was signaled in green. When the subject hit the first signaled key, the subject′s session timer was started. Only if the subject hit a key in the right way, the next random key was signaled. After 22 s or by operator′s manual command, the session stopped. Under 1G conditions the operator started and stopped the system manually. For scheduling the experiment session in flight we timed our procedure strictly by the pilot′s audio announcements of trajectory: ”Pull Up” (increased Gz-load up to 1.8G) and ”Injection” (rapid fell G_z-load to ≈0G).

The study consists of two independent variables (BA, PA) on four acceleration levels (1G PRE, 1.8G, 0G, 1G). In a within-subject design, each participant performed the test series for all independent variables in all levels that resulted in a factorial design of 4 x 2. The task repeating rate for each method amounted to seven times at each level. That resulted in 8 x 7 (i.e., each subject performed 56 test series). Overall, 336 data samples (252 in flight, 84 on ground in aircraft) were expected. To ensure the functional capability under the strict experimentation conditions we could not use variations of the presentation order for counterbalancing of

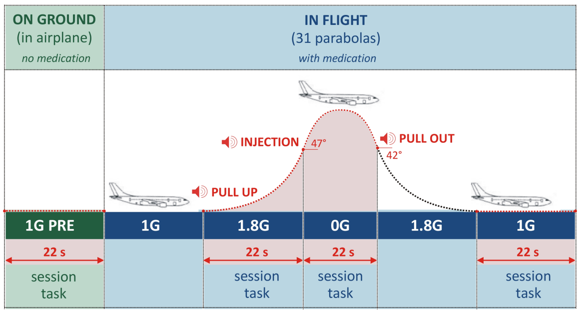

Figure 5: *The characteristics of the gravitational levels.*

the methods in flight between the parabolas (i.e., one subject performed one method for seven parabolas in series). But generally the presentation order of the methods was varied systematically and the methods were changed in the 8^{th} and 23^{rd} parabola (see Fig. 1). The subjects were changed in the 8 min break.

3. Measurements and Data Analysis

To evaluate the efficiency of the methods (BA, PA), four different types of measures were used: (1) pointing performance, (2) pointing accuracy, (3) physiological workload, and (4) subjective workload. The pointing performance was measured by subject$'$s overall completion time of one test series, by hit key response times and the frequency of correct and incorrect pointing. The pointing accuracy at hitting a correct key was measured by the Euclidean distance $d_{correct}$ between the signaled key origin $P_{signaled}$ and the point of intersection $P_{correct}$. For measuring the physiological workload, the HRV sensors recorded the heart rate variability and 3-axis acceleration at a sampling frequency of 1000 Hz and an accuracy of 1 ms. Subjective measurements were collected by several rating scales. The subjective workload was measured with the standardized NASA RTLX (Raw Task Load Index) and contains the same items as the NASA TLX, but without the paired comparison stage [BBH89]. Thereby the subject had to rate their mental, physical and temporal demand, performance, effort and frustration level after performing the tests by one method on a continuous rating scale from very low to very high. For descriptive statistical analysis we present the median, the standard deviation (SD), the Interquartil range (IQR), the minimum and the maximum. For pointing performance we show the frame rate, completion time, the percentage pointing error rate, the stroke rate and the frequencies of correct and false key hits using the complete model of method, level and their interaction *method*level*. We have performed several statistical tests for the pointing performance, accuracy and subjective workload. Thereby the significance level was set at $p < .05$. Although the number of subjects is low, the data are high correlated and the influence of systematic errors was avoided by the randomized presentation order of the key pools.

4. Results

We could evaluate the expected number of data sets of 336 (252 in flight, 84 on ground in aircraft). The experimentation system worked very well at an overall median frame rate of 40.98 frame per second (SD=11.84, IQR=24.01). The averaged frame rate using the BA method (45.98 fps, SD=11.88) was 10.01 fps higher than the PA method (35.97 fps, SD=11.0) caused by a more comprehensive marker configuration. Due to the fact that the experimentation area inside of the Zero-G aircraft does not support daylight and provide stable lighting conditions, the optical marker-based tracking system worked very stable and did not require additional adjustment of the video lighting threshold value during operation. Both methods (BA, PA) were applicable under all gravitation level. The task of typing random letters was performed by each subject under both keyboard configurations in all levels successfully (see Fig. 2). No subject suffered from motion sickness.

4.1. Pointing Performance

Completion time: The timer of a session was started manually by the operator and was running for maximal 22 s or stopped by the operator. The timer of the subject was started after the subjects entered the first signaled key. This resulted in different completion times of the subjects. The subjects performed the test series with an overall median completion time of 19.94 s (SD=2.06), the BA method with median 20.25 (SD=1.82) and the PA method with a median time of 19.44 s (SD=2.20). Figure 6 and Table 4 show subject completion times presented by the interaction *method*level*. The test series performed with the BA method under 0G lasted averaged longer with 2.05 s than the performance with the PA method and under 1.8G 0.89 s longer. Lower completion time was caused either by the subjects$'$ with delayed entering of the first key or by the operator resulted from a delayed session start.

Key response time: The median key response time over all subjects evaluated without false key hits was nearly the same for both method under all gravitational levels. Using the BA method led to an averaged key time of 1.25 s (SD=0.36) and for the PA method to averaged 1.26 s (SD=0.40) with nearly the same spreading for both methods. Interesting are subjects$'$ response times of entering the first signaled key (see Table 2). While the subjects entered the first signaled key using the BA method after averaged 1.40 s (SD=0.97), with the PA method the subjects entered only after 1.88 s (SD=1.55). The median response time under 0G using the PA method resulted in almost doubled from the time using the BA method. That was caused by longer orientation processes of the subjects towards the outside physical surface and has influenced the completion time of the subjects. The fastest key response time to the first signaled key was achieved using the BA method under 1.8G.

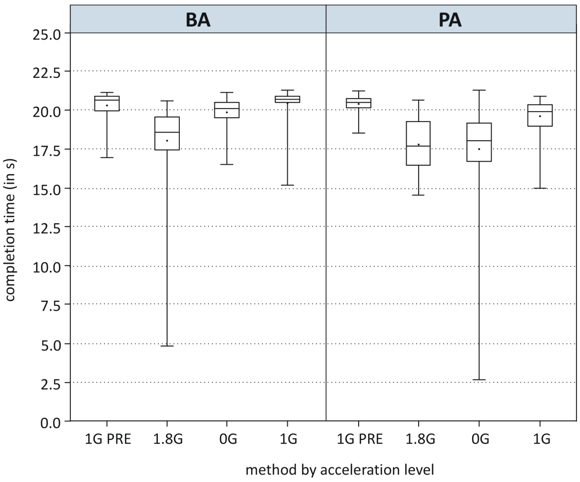

Figure 6: *Subjects′ completion time.*

Method by level	Response time to first key hit (s)			
	median±SD	IQR	min	max
BA_1G PRE	1.37±0.88	0.91	0.87	5.04
BA_1.8G	**1.27**±0.94	0.79	0.89	5.75
BA_0G	1.87±0.94	0.93	0.60	5.47
BA_1G	1.32±1.07	0.37	0.72	6.80
PA_1G PRE	1.51±0.05	0.57	0.78	3.50
PA_1.8G	1.67±0.92	0.66	1.03	5.10
PA_0G	**3.86**±1.92	2.54	0.72	7.97
PA_1G	2.06±1.21	1.26	1.08	7.05

Table 2: *Median response time for entering the first key.*

Key hits of methods by gravitation (Fig. 7)**:** A total of 4965 keys were entered with 4390 correct hits with a median of 13 keys (SD=3.45) per test series and 575 false hits with a median of 1 key (SD=1.95) that results in a total pointing error rate of 11.58 %. At different subject completion times the subjects entered 2603 keys with 2393 correct hits with a median of 15 keys (SD=2.84) per test series and 210 false hits with a median of 1 key (SD=1.49) using the BA method that results in total pointing error rate of 8.06 %. Using the PA method 2362 keys were entered with 1997 correct hits with a median of 12.5 keys (SD=3.62) and 365 false hits with a median of 2 keys (SD=2.22) , which led to a total error rate of 15.45 %. The highest number of correct hits was achieved under 1G in flight with the BA method with 664 correct key hits and a total pointing error rate of 4.73 %. With the PA method performed under 0G, the lowest number of correct hits with 381 and an error rate of 29.96 % was achieved. Table 5 shows the total and median number of correct and false hits with its total percentage pointing error rate for both methods by each level. Comparing the performance under 1.8G and 0G, with the BA method under 0G led to more correct hits with 573 but more false hits with 90 (13.57 % error rate), than under 1.8G with 564 correct and 50 false hits (8.14 % error rate). In contrast, the PA method led to more correct hits under 1.8G with 448 and less false hits with 107 (19.28 % error rate) than under 0G with 381 correct and 163 false hits (29.96 % error rate). Overall the data suggests that the performance related to the pointing error rate under 1.8G and 0G of 17.86 % was down to a third compared to the error rate under normogravity (1G PRE, 1G) of 6.37 %. Separated by the methods, the performance related to the error rate was reduced by half for the BA method and down to a third for the PA method under altered gravity (1.8G, 0G).

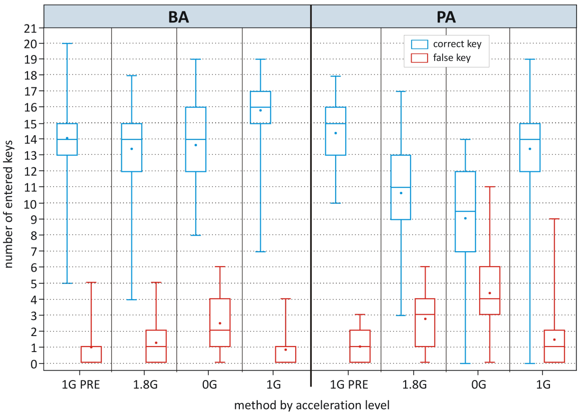

Figure 7: *Correct and false keys of method by gravitation.*

Method by level	Correct key hits	False key hits	Error
	total[median±SD]	total[median±SD]	(%)
BA_1G PRE	592 [14±2.9]	37 [1±1.2]	5.9
BA_1.8G	564 [14±2.9]	50 [1±1.4]	**8.1**
BA_0G	573 [14±2.9]	90 [2±1.7]	**13.6**
BA_1G	664 [16±2.4]	33 [1±0.9]	4.7
PA_1G PRE	604 [15±2.1]	39 [1±1.1]	6.1
PA_1.8G	448 [11±3.3]	107 [3±1.5]	**19.3**
PA_0G	381 [9.5±3.2]	163 [4±2.6]	**29.9**
PA_1G	564 [14±3.1]	56 [1±1.6]	9.0

Table 3: *Pointing error rate by correct and false key hits.*

Considering subject completion times correlated with the correct hits, the corresponding stroke rates are presented in Table 6. The subjects performed the task with the highest median rate of 0.77 s^{-1} under 1G in-flight using the BA method and the lowest rate of 0.53 s^{-1} under 0G with the PA method. The performance related to the key stroke rate was slowest under 0G for both methods [MBM*02]. It is interesting that the performance with the BA method under 1.8G was faster than under normogravity on ground (1G PRE) and very close to the value under 1G in-flight. This suggests that the performance related to the stroke rate is of no considerable difference between normo- and altered gravity with using the BA method. In contrast to this, the PA method differed. While under normogravity (1G PRE, 1G) the subjects performed nearly with an equal high stroke rate, under altered conditions (1.8G, 0G) it was decreased.

Method by level	**Subject′ completion time** (s)				**Stroke rate** (s^{-1})
	median±SD	IQR	min	max	
BA_1G PRE	20.64±0.29	0.91	16.98	21.13	0.68
BA_1.8G	18.60±0.36	2.44	4.81	20.62	**0.75**
BA_0G	20.12±0.45	0.97	16.54	21.17	0.69
BA_1G	20.69±0.29	0.37	15.20	21.29	0.77
PA_1G PRE	20.52±0.41	0.56	18.52	21.24	0.73
PA_1.8G	17.73±0.43	2.76	14.52	20.66	0.62
PA_0G	18.07±0.39	2.36	2.65	21.33	**0.53**
PA_1G	19.94±0.41	1.26	14.97	20.92	0.71

Table 4: *Stroke rates by subjects′ completion time.*

Statistical analysis: We have statistical analyzed the relative frequencies of the number of correct and false key hits in consideration of the Logit transformation as Link function and the binomial distribution as probability distribution depends on the methods, the gravitation levels, and their interaction. Based on an overall interaction, we performed comparisons on same method stage (BA, PA) and same level stage(1G PRE, 1.8G, 0G, 1G) using the Chi-square-homogeneity test (Proc. GENMOD, SAS 9.3).

The comparison of the levels on same method stage for correct (Table 5) and false key hits (Table 7) resulted in significant differences for all in-flight levels (1.8G, 0G, 1g). The 1.8G and 0G levels (1.8G, 0G) using the BA method differs significantly with p=0.0019 < *.05* and PA with p=0.0002 < *.05* for correct keys, and BA with p=0.0020 < *.05* and PA with p=0.0002 < *.05* for false keys. Comparing the normogravity conditions (1G, 1G PRE) on same method stage, there was no significant differences for correct and false key hits. Performing the test by comparing the methods BA and PA on same level stage for correct (see Table 6) and false key hits (Table 8) resulted also in significant differences for all in-flight levels (1.8G, 0G, 1G): < .0001 on 1.8G and 0G, and p=0.0074 < *.05* on 1G for correct and false key hits. The comparison of the methods BA and PA under normogravity on ground (1G PRE) showed no significant differences for correct and false key hits.

4.2. Pointing Accuracy

For evaluating the pointing accuracy we use the Euclidean distance $d_{correct}$ between $P_{signaled}$ and $P_{correct}$ for correct hits. The performance with the BA method led to more accurate correct hits under all gravitational levels than the PA method. Related to the 1.8G and 0G, the most accurate hits were achieved under 1.8G, while the performance under 0G led to more inaccuracy pointing. While under normogravity (1G PRE, 1G) using the PA method the median distance showed no differences, using the BA method resulted in more accurate hits under 1G in flight.

Levels		**Method**	**Lower**	**Upper**	**p value**
1G	1G PRE	BA	-0.3139	0.8178	0.3828
1.8G	1G	BA	-1.1223	-0.0539	**0.0310**
0G	1G	BA	-1.7384	-0.7732	**< .0001**
0G	1.8G	BA	-1.0900	-0.2453	**0.0019**
1G	1G PRE	PA	-0.9286	0.0636	0.0875
1.8G	1G	PA	-1.3014	-0.4939	**< .0001**
0G	1G	PA	-1.9028	-0.1346	**< .0001**
0G	1.8G	PA	-1.9446	-0.2975	**0.0002**

Table 5: *Analysis of correct keys by comparing the levels on same method stage.*

Methods		**Level**	**Lower**	**Upper**	**p value**
BA	PA	1G PRE	-0.5117	0.5716	0.91
BA	PA	1.8G	0.6050	1.4429	**< .0001**
BA	PA	0G	0.6494	1.3054	**< .0001**
BA	PA	1G	0.1920	1.2368	**0.0074**

Table 6: *Analysis of correct keys by comparing the methods on same level stage.*

For statistical analysis we have applied variance analysis for the feature $d_{correct}$ of correct key hits by the complete model connected with the t-test as comparison of means. We have performed the comparison of the method on same level stage over all subjects (see Table 9). At this differentiation, the methods BA and PA differ significantly to each other for all in-flight levels (1.8G, 0G, 1G). The performance under normogravity on ground and without medication (1G PRE) showed no significant differences.

4.3. Physiological Workload

The HRV data was assessed during the experiment in upright posture and a number of HRV parameters were calculated. Regarding the strain index in this context, the data show (see Table 11) that the physiological and cognitive workload was at the lowest point for the subjects during the inactive phase of the experiment, except one subject, who was unexperienced in parabolic and suffered a panic attack initially, but calmed down before starting the experimentation after the 15th parabola. Furthermore the results suggest that the workload was higher during the application of the BA mode for five subjects. Caused by the inter-individual characteristics, one subject was more strained using the PA method.

4.4. Subjective Workload

All subjects rated their workload after changing the methods in 1G PRE and after the in-flight test series at once

Levels		**Method**	**Lower**	**Upper**	**p value**
1G	1G PRE	BA	-0.8183	0.3144	0.3832
1.8G	1G	BA	0.0534	1.1228	**0.0311**
0G	1G	BA	0.7727	1.7388	**< .0001**
0G	1.8G	BA	0.2449	1.0904	**0.0020**
1G	1G PRE	PA	-0.0906	0.9100	0.1085
1.8G	1G	PA	0.4936	1.3017	**< .0001**
0G	1G	PA	1.1343	1.9032	**< .0001**
0G	1.8G	PA	0.2972	0.9449	**0.0002**

Table 7: *Analysis of false keys by comparing the levels on same method stage.*

Methods		**Level**	**Lower**	**Upper**	**p value**
BA	PA	1G PRE	-0.5983	0.4929	0.8498
BA	PA	1.8G	-1.4433	-0.6046	**< .0001**
BA	PA	0G	-1.3057	-0.6491	**< .0001**
BA	PA	1G	-1.2372	-0.1916	**0.0074**

Table 8: *Analysis of false keys by comparing the methods on same level stage.*

Methods		**Level**	**Lower**	**Upper**	**p value**
BA	PA	1G PRE	-0.4225	0.0713	0.1633
BA	PA	1.8G	-1.1573	-0.6170	**< .0001**
BA	PA	0G	-1.2670	-0.7026	**< .0001**
BA	PA	1G	-1.3878	-0.8989	**< .0001**

Table 9: *Analysis of Euclidean distance $d_{correct}$ by comparing the methods on same level stage.*

ID	**Gender**	**Height** (cm)	**Weight** (kg)	**PF exp.**	**Strain Index** (SI)		
					inact.	**BA**	**PA**
S1	female	171	90	no	81.55	104.34	117.47
S2	male	185	82	yes	35.28	54.75	40.19
S3	male	171	78	no	30.29	36.30	35.33
S4	male	172	69	yes	78.22	174.76	155.13
S5	male	180	107	no	332.23	196.82	170.56
S6	male	188	80	yes	65.93	110.10	95.96

Table 10: *Subjects$'$ inter-individual characteristics, the PF experiences and the strain indexes for the inactive, the BA and the PA phase.*

by the NASA RTLX. All items of the subjective workload were least rated under normogravity on ground (1G PRE). Comparing the methods under 1G PRE, nearly all items (except mental demand and effort) were rated higher for the BA method. The data show that the workload under the in-flight conditions (1.8G, 0G, 1G) was increased clearly by the PA method. We also statistical analyzed the NASA RTLX scale by a non-parametric test using the Wilcoxon Rank Sum test that investigates differences in medians, with the assumption of identical spreads. The test results in significant differences at the in-flight levels with p=0.0005 $< .05$ with a mean score of 28.01 for the BA method and 44.97 for the PA method. For the 1G PRE level the test result in p=0.4015 with a mean score of 35.88 for the BA method and 37.125 for the PA method.

5. Discussion and Future Work

We investigated the effect of altered gravity on goal-directed pointing movements in response to visual stimuli performed in a head-mounted AR environment. In particularly we compared two methods of coding the pointing target related to the human body frame of reference operated under normo,- hyper- and microgravity. Thereby we distinguished between targets coded inside and outside of the body frame. While the inside method denotes a bi-manual handling of the pointing interface, the outside method requires a preliminary orientation process. To verify our hypothesis that the performance of aimed pointing movements towards inside located targets increase the efficiency and decrease the workload under hyper- microgravity, we conducted a within-subject study under parabolic flight conditions. We were able to show a significant effect of altered gravity on aimed AR pointing movements in response to visual stimuli. While the overall response time for pointing toward a single target do not differ under normo- and altered gravity regardless of target$'$ location, longer orientation processes towards targets coded outside human body frame of reference increase the response times for entering the first target, especially under microgravity. By distinguishing correct and false hits, the performance under hyper- and microgravity leads to a pointing error rate of approx. down to a third compared to the error rate under normogravity regardless of target$'$ location. Related to the location of the targets, we found out that pointing towards targets coded inside human body frame of reference reduces the error rate by half. Pointing towards targets coded outside of the frame reduces the error rate down to a third compared to the error rate in normogravity. Related to the stroke rate we could not detect effects of altered gravity for aimed pointing movements performed inside the human body frame of reference. Pointing towards target coded outside of the body frame decrease the stroke rate. Statistical tests have shown that aimed pointing movements related to the frequencies of correct and false hits in normogravity on ground (1g PRE) and in flight (1G) do not change significantly, regardless of target$'$ location (BA, PA). But the performance differ significantly between the gravitational level in flight (1.8G, 0G, 1G) for the inside and outside location. Also we found out that pointing movements performed under altered gravity in flight (1.8G, 0G, 1G) also differ significantly in the location of the target related to human body frame of reference. Accordingly, the data suggests that aimed pointing performed towards target coded inside human body frame of reference lead to significantly more accurate performance under altered gravity in flight than towards targets coded outside. For performances in normogravity on ground (1G PRE) the pointing accuracy differs not significantly between target′ coding. Even though the analysis of the performance and accuracy have shown that using the BA method is more efficient than the PA method, the evaluation of the physiological workload by HRV analysis has shown that the subjects were more strained using the BA method. Due to bi-manually operating of the BA panel the physical effort caused higher heart rate leading to lower heart rate variability and implying higher strain. In contrast, the subjective workload in flight was significantly higher by using the PA method, but slightly lower under normogravity on ground. Related to our hypothesis we could show that aimed pointing movements towards inside coded target increases the performance and decreases subjective workload under altered gravity compared to pointing towards outside coded targets. This suggests that future AR pointing interfaces used under altered gravity, e.g. for symbolic input or system control, should be designed inside human body frame of reference. Given that main applications of operating an ISS payload are located outside of the human body reference system, the visual-motor performance need to be optimized by developing adequate countermeasures. To compensate the deficit, we propose a gravity-adopted approach for the view management that we will test in a proof-of-principle study performed at a short-arm human centrifuge.

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