Virtual reality as training aid for manual spacecraft docking

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ABSTRACT

The ability to manually dock a spacecraft to a space station can be crucial for astronauts during space missions. The computer-based self-learning program *6df* is an abstract docking simulation for acquisition and maintenance of the underlying skill to control six degrees of freedom. One of the difficulties of this complex task is to construct a mental representation of the own position and orientation in space, based only on two-dimensional information. To facilitate this and possibly further improve the learning process, a new three-dimensional (3D) stereoscopic presentation of the program is tested. This study investigates whether there is faster learning progress with 3D presentation compared to standard 2D presentation. 24 participants of the Artificial Gravity Bed Rest Study with ESA (AGBRESA) participated in the *6df docking* experiment. Each of them completed 20 training sessions which lasted approximately 45 min and were conducted twice a week. The learning program is self-sufficient and adapts itself to individual learning speed. Half of the participants were presented with an UNITY-based stereoscopic visualization of docking, whereas the other half used the standard 2D version of the learning program *6df*. Learning progress was measured as the number of tasks needed to reach a target task. Results overall indicate a slightly faster learning progress when using 3D technology, but no long-term performance advantages. The small benefit might not justify the usage of costlier and operationally limiting 3D systems.

1. Introduction

Manually controlled docking of a spacecraft to a space station can be crucial for space mission safety, as automatic docking may fail or more flexibility may be needed [1,2]. The complex task requires the ability to proficiently control objects in six degrees of freedom (DoF), which is almost unique to space. In space, objects can be moved along three axes (translation) and rotated around each axis (orientation). During docking, the left hand control operates three DoF of translation (movement along x-, y- and z-axis) and the right hand control three DoF of rotation (controlling yaw, pitch and bank). In contrast, when driving a car, only two DoF have to be controlled. The ability to control six DoF has to be trained intensely on simulators and with experienced instructors. The task is challenging, as internal frames of reference have to be constructed, i.e. a representation of one's own position, orientation, and motion within the physical environment. New cognitive, perceptual, and motor skills have to be acquired. The two hand controls have

distinct functionalities: the translation control resembles a set of on-off switches and each impulse must be compensated with an equally strong impulse in the exact opposite direction to stop the movement. Thus, stabilizing the spacecraft in all axes is demanding. By contrast, the orientation hand control is an analogous one. The difficulty here is that handling is counterintuitive for most people, as the hand control must be moved to the right if one wants to turn left. All these challenges occur in addition to the adverse conditions of space flight, which may impair performance in astronauts and cosmonauts with potentially fatal consequences. Indeed, according to Ellis [2], workplace stress, sleep deprivation, and insufficient training for skill maintenance predisposed to an accident during manual docking in 1997.

We developed the *6df* training tool to facilitate acquisition and maintenance of the complex manual ability of controlling six DoF [3]. The learning program acquaints participants without prior knowledge to the handling of six DoF and features individually paced self-learning without an instructor. Moreover, the tool is designed for continuous

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training to maintain docking skills on a safe level, for example during long term space flights. Furthermore, the learning process and operator's skill can be investigated simultaneously, as in a previous study by Johannes et al. [4]. In this study, all participants were able to perform a standard docking maneuver task following the *6df* course. However, some needed considerably more training time and repetitions. Therefore, we were interested in methodologies to further enhance learning and training efficiency. Constructing an appropriate frame of reference is critical for learning success and has to be newly learned in space, as there is no fixed plane for orientation. Additionally there is another difficulty: manual docking is based on a two-dimensional screen that impedes perception of one's own position and spatial relations. We reasoned that perception of relations in space and training efficiency could be improved using a three-dimensional (3D) stereoscopic version of the *6df* learning program as a desktop-based virtual reality (VR) approach.

A plethora of 3D and virtual reality applications have been designed in the past years, not only for entertainment purposes. Fuchs, Moreau, and Guitton [5] provide a definition of VR as a computer-based simulation of the behavior of 3D entities in a virtual world, which interact with the user in real time via sensorimotor channels. According to Freina and Canessa [6], different levels of immersion are possible, which can create a feeling of actual presence in the virtual world. As Freina and Ott [7] review, VR methodology has been discovered for educational purposes in many different fields. In medical training for example, Seymour summarizes VR to provide effective skill transfer into the operating room [8]. In space flight contexts, "real-life training" is often expensive, demanding for large facilities or even impossible, therefore VR is used to efficiently extend astronaut training possibilities [9–13]. For example, Aoki and colleagues tested a VR navigation training for facilitating orientation within International Space Station in the case of an emergency egress [14,15]. Olbrich et al. [16] followed a similar idea with the development of a VR environment that allows astronauts to train for a possible case of fire emergency in a simulated lunar base. Another VR training application, examined by Stroud, Harm and Klaus [17], has been the prevention of motion sickness and spatial disorientation in space. Bosch Bruguera, Ilk, Ruber and Ewald [18] lately developed their Soyuz spaceflight simulator by adapting it for future missions with the Russian Spacecraft "Federatsiya" to Lunar Orbital Platform – Gateway and by adding immersion using a VR headset and hand tracking. Their approach is focused on achieving high graphical and physical realism.

We tested the hypothesis that stereoscopic presentation of the learning program will enhance participants' ability to understand spatial relations, and thereby the construction of an appropriate frame of reference. More precisely, we anticipated that additional spatial information should facilitate mental representation of spatial relations, and eventually lead to faster learning progress compared to the standard 2D view. We had the unique opportunity to test our approach in the setting of a head-down tilt bed rest study, which is an established terrestrial model for microgravity [19,20]. Our primary goal is the development of a tool that is applicable in space. After *6df* has been tested for general suitability as a learning tool [4], we wanted to show that it would be likewise applicable under space analog conditions.

2. Material and methods

2.1. Participants

24 healthy individuals (8 women and 16 men, 24–55 years old) participated in our experiment, which was part of the "Artificial Gravity Bed Rest study with European Space Agency" (AGBRESA) at the :envihab facility of the Institute of Aerospace Medicine at the German Aerospace Center (DLR) in Cologne, Germany. AGBRESA was a large joint project of ESA, NASA, and DLR, designed to accumulate knowledge about the effects of microgravity in an experimental ground-based analog environment for long-term human spaceflight. The study was prospectively registered with the German register for clinical studies (www.drks.de) with the identifier DRKS00015677 and comprised two campaigns (March–June and September–December) in 2019 with twelve participants each. After 15 days of familiarization and baseline measurements, participants spent 60 days in 6° head-down tilt bed rest to simulate the effects of microgravity and to explore the effectiveness of short-arm centrifuge training as a countermeasure against degradation processes in weightlessness. After re-ambulation, participants stayed in the facility for another 14 days of regeneration and post measurements. Our sub-study consisted of a training course on how to maneuver an object with six DoF using the *6df* tool. One of the participants first used the Russian version of the learning program, but switched to the default German version later during the course. Another participant chose the English version of the instructions. Participants were granted monetary compensation for the whole bed rest study. The study has been approved by the ethics committee of the medical association North-Rhine in Dusseldorf, Germany and participants provided written informed consent.

2.2. Docking task

The training tool named *6df* used in this experiment has already been described in detail and tested for applicability before by Johannes et al. [3,4]. In short, *6df* is a computer-based and self-sufficient learning program that simulates the control of an object with six DoF, in this case the manual docking of a spacecraft to an abstract space station. Flight dynamics and controller responsiveness are based on the Russian docking training system TORU (Teleoperatiya Ruchnogo Upravleniya – teleoperated manual control) and the actual Soyuz spacecraft. However, the tool is not designed to be a realistic Soyuz simulation, but to teach the principles of the control of any object in space abstractly. Participants are first familiarized with the controller handling and are then gradually instructed to control up to six DoF. Each task starts with an illustrated instruction text, sometimes including example videos. After each task, feedback about various specific parameters such as forward speed, pitch, bank, and yaw is given, as well as an aggregated general performance measure, with zero being the worst and 1.0 the best possible accuracy, following TORU methodology [21]. The program adapts to individual learning speed, so that tasks are repeated when errors occur. If a task is mastered with a general performance score of at least 0.95, the next (and more difficult) task is presented. The program is structured in twelve ascending levels labeled between 1 and 60, most of them containing a small number of different tasks that are similar in difficulty. At the end of the learning program participants should be able to dock a virtual object to the docking point in a standard docking maneuver including flight-around, stabilization on the center line and final approach. The *6df* software was developed by SpaceBit GmbH (Eberswalde, Germany) and hand controls were produced by Koralewski Industrie-Elektronik oHG (Hambühren, Germany).

2.3. Setup and procedure

During experimental sessions, participants remained in a 6° head-down tilt position without a pillow. A computer screen was attached on a rack above the participants' heads at a distance of approximately 60 cm to present the *6df* training program. Hand controls for docking were also mounted to the rack so that they could be used conveniently in a lying position. Complete laboratory setup and equipment is illustrated in Fig. 1. Each participant completed at least twenty *6df* training sessions, each of which took approximately 45 min. In an earlier study using *6df*, an average of 20 sessions sufficed to pass the course and reach the standard docking level [4]. Sessions were scheduled on average twice a week during the study course, three sessions before bed rest and the remaining sessions during the 60-day bed rest period. Sessions were minimally one day and maximally seven days apart, but the usual interval was every three to four days. Each single docking task comprised

Fig. 1. Laboratory setup for the stereoscopic *6df* version in 6° head-down tilt.

up to 12 min without instructions and feedback, depending on level and participant's speed. The number of tasks in each session also varied depending on these factors. Participants in each campaign were randomly assigned to two groups: one group was presented with the conventional two-dimensional learning program, and the other group used a newly designed stereoscopic *6df* version. Therefore, in each campaign six participants were assigned to the stereoscopic version and six participants to the standard program. The 3D program was equivalent to the standard version, but displayed a three-dimensional view of visor and station based on *Unity* (Unity Technologies, San Francisco, CA, USA). The visor resembles a cross to target the docking point and adjust the orientation of the spacecraft to the station. Participants wore *Nvidia 3D Vison 2* wireless glasses (Nvidia Corporation, Santa Clara, CA, USA). Because a docking maneuver in space has to be performed based on a two-dimensional screen, the stereoscopic view only supported the first learning steps. Three-dimensional viewing was only used until a participant reached the task in the middle of level 15. After achieving this landmark, the program automatically switched to the standard two-dimensional view, so conditions were similar for both groups thereafter and the 3D group would be able to adjust to 2D view during the rest of level 15. Level 15 was chosen because the stabilization and correct orientation of the spacecraft previous to the final docking approach are trained. To stand still in open space is of high difficulty, an important milestone in the learning process and necessary to solve all following tasks. We assumed that the new technology might be most helpful up to that point, but should then be omitted to familiarize participants with the standard two-dimensional presentation, as in reality docking is also based on a 2D screen.

On the day after being released from bed rest (five days after the last *6df* training), we verified learning success in an additional session. This session contained a fixed series of five docking tasks of the Russian training system TORU that was provided by S.P. Korolev Rocket and Space Corporation Energia, Korolyov, Russia. TORU tasks applied the same hand controls and require identical skills to control six DoF based on the Soyuz spacecraft. Nevertheless, these tasks are more demanding, as they additionally take into account orbital mechanics and spacecraft inertia. The same procedure was applied for regular cosmonaut training onboard the International Space Station 2008–2011 [21].

2.4. Data analysis

For data processing and statistical analysis, we applied *SPSS Statistics 21* (IBM, Armonk, NY, USA). Some levels include a predefined flight path, marked with rings the participants had to move through without touching – otherwise the task is terminated. Excluded from the analysis were 256 attempted tasks that ended in such a ring collision. We operationalized learning speed using the number of tasks "flown" by the subjects. As *6df* is adaptive, fewer tasks up to a criterion task or level mean fewer errors, faster progress through the program and therefore faster learning. The dependent variable of interest was, therefore, how fast, which means after how many tasks, participants reached the critical task on level 15. Since the number of tasks was significantly non-normally distributed according to Kolmogorov-Smirnov test ($D = 3.32$, $p < .001$), we compared learning speed between 2D and 3D group using the nonparametric Mann-Whitney test. In the same way we also tested if there was a difference in the number of tasks needed from the beginning of the program up to level 60, which resembles a standard docking maneuver in space and is therefore the end of the learning program. This was done in order to test whether the initial 3D-training had any longer lasting effects on the learning process. Cohen's d is reported as measure of effect size. Additionally we also applied a multilevel linear mixed effect model (LME) to the data to test the effects on the number of tasks (learning speed) throughout all training sessions. For this purpose raw data were approximated to normal distribution as far as possible using Box-Cox transformation ($D = 2.84$, $p < .001$). Another eight tasks were excluded as extreme outliers (task number values more than three standard deviations above mean). Thereby, we achieved normal distribution of residuals for LME modelling. The model included level, group (2D or 3D), campaign (spring or autumn) gender and age (median split: ≤ 33 and >33 years old) as fixed effects, as well as the interactions of level with group and level with gender. Participants were included as a random effect using *variance components* as covariance structure. The model was applied to the whole learning data as well as separately to both training halves before and after the switch from 3D to 2D. Finally TORU data were analyzed to test whether 3D visualization would influence not only learning speed, but final docking performance after the course. The TORU docking performance score (ranging from 0 to 1.0) was the dependent variable of this LME. Group and the interaction of group with TORU task (1–5) were included as fixed effects, participants

as random effect.

3. Results

Overall, participants completed 3395 valid training tasks. On average, participants of the 2D group "flew" $M = 89.67$ tasks (Median = 81.50, $SD = 32.33$) before reaching the shift task from 3D to 2D on level 15, whereas participants of the 3D group required on average $M = 76.17$ tasks (Median = 78.50, $SD = 11.65$) (see Fig. 2). Although 3D participants did learn faster descriptively, the difference between the two groups was not statistically significant ($U = 59.00, z = -0.75, p = .45, d = 0.55$). Regarding learning speed up to the final standard docking maneuver, 2D participants completed on average $M = 147.75$ (Median = 151, $SD = 18.40$) tasks and 3D participants $M = 140.58$ tasks (Median = 136.50, $SD = 25.65$) (see Fig. 3). Likewise, the Mann-Whitney test did not result in significant group differences ($U = 56.50, z = -0.90, p = .37, d = 0.32$).

A descriptive view on the learning process based on all single levels (Fig. 4) reveals that 3D participants on average needed fewer tasks to
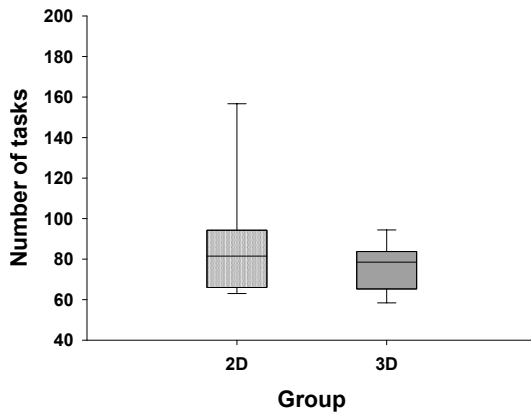

Fig. 4. Average number of tasks needed to reach each *6df* level by experimental group. Whiskers indicate 95% confidence interval.

Fig. 2. Learning speed until the criterion task on level 15 by presentation group. Depicted are the median number of tasks, the interquartile range (box) as well as minima and maxima (whiskers).
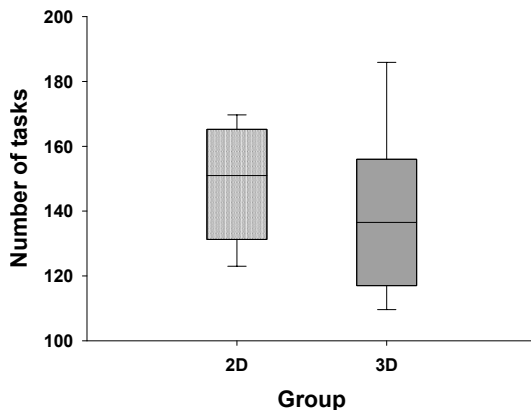

Fig. 3. Learning speed until the end of the learning program by presentation group. Depicted are the median number of tasks, the interquartile range (box) as well as minima and maxima (whiskers).
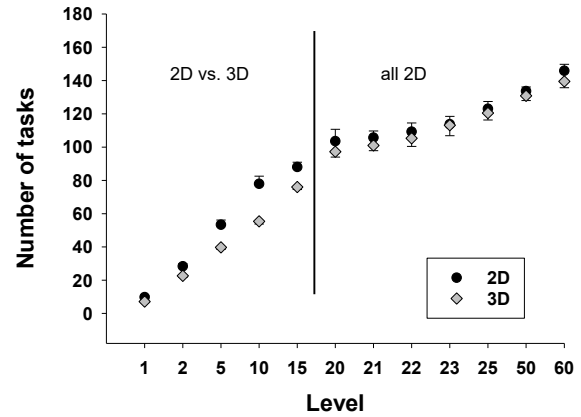
reach every level in comparison with the 2D group; especially during the 3D phase up to level 15. Yet, after switching to 2D, differences between groups were only marginal. Therefore, we assessed the whole learning process using LME to further clarify the results. Not surprisingly, level predicted the number of tasks significantly for the whole learning program ($F(11, 3338.57) = 4215.41, p < .001$) as well as for the first 2D vs 3D half ($F(4, 1867.69) = 2910.58, p < .001$) and the second all 2D portion of the training program ($F(7, 1447.39) = 1202.34, p < .001$); as participants did ascend to higher levels with increasing task number. There was no significant main effect of campaign in any model (whole course: $F(1, 18.98) = 0.10, p = .75$; first half: $F(1, 19.14) = 0.07, p = .79$; second half: $F(1, 18.89) = 0.20, p = .66$), and, therefore, no differences in learning speed between study cohorts. 2D/3D group did not predict learning speed, neither for the whole program ($F(1, 19.09) = 0.17, p = .68$), nor for the first 3D half ($F(1, 19.14) = 0.52, p = .48$) or the second section after switching to 2D ($F(1, 18.91) = 0.04, p = .85$). Although there was no main effect of the 3D presentation, the interaction of level with group did predict the number of tasks for the whole program ($F(11, 3338.54) = 3.55, p < .001$) as well as for the first portion of the program ($F(4, 1867.91) = 9.51, p < .001$). However, there was no significant interaction for the second half of the training alone ($F(7, 1447.28) = 1.03, p = .41$). The efficacy of 3D presentation in augmenting learning speed is, therefore, dependent on task difficulty level – and is not carried over into the all 2D training phase.

The model also included age and gender as possible predictors. Age had a significant main effect in all models (whole course: $F(1, 18.98) = 7.80, p = .01$; first half: $F(1, 19.12) = 5.34, p = .03$; second half: $F(1, 18.88) = 8.67, p = .01$). As shown in Fig. 5, younger participants did learn faster in comparison to older participants. Gender predicted the number of tasks significantly for the whole program ($F(1, 19.11) = 5.39, p = .03$) as well as for the second portion ($F(1, 18.97) = 5.80, p = .03$); but not for the first portion of the learning program ($F(1, 19.08) = 2.83, p = .11$). The interaction of level with gender, however, significantly predicted number of tasks in all models (whole course: $F(11, 3338.62) = 34.00, p < .001$; first half: $F(4, 1867.82) = 65.42, p < .001$; second half: $F(7, 1447.43) = 5.75, p < .001$). Whereas there was barely a gender difference during the very first levels, men did learn faster than women in the middle and higher difficulty ranges (see Fig. 6).

Fig. 7 illustrates performance in the five Russian TORU docking tasks. For the first three tasks, the stereoscopic group's average
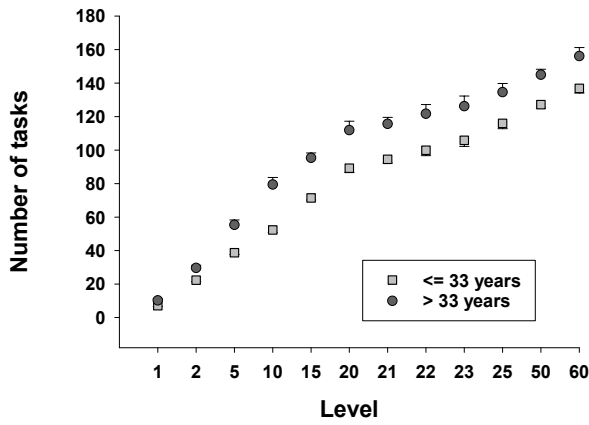
Fig. 5. Average number of tasks for each *6df* level by age group (33 years or younger; older than 33 years). Whiskers indicate 95% confidence interval.

performance scores were higher than those of the 2D group; for the last two tasks there was no difference. Averaged over all TORU tasks 3D participants achieved a performance score of $M = .86$ and 2D participants of $M = .81$. The LME resulted in no significant main effect of 2D/3D group ($F(1, 21.78) = 0.58, p = .46$). However, there was a significant interaction of TORU task and group, which predicted the performance
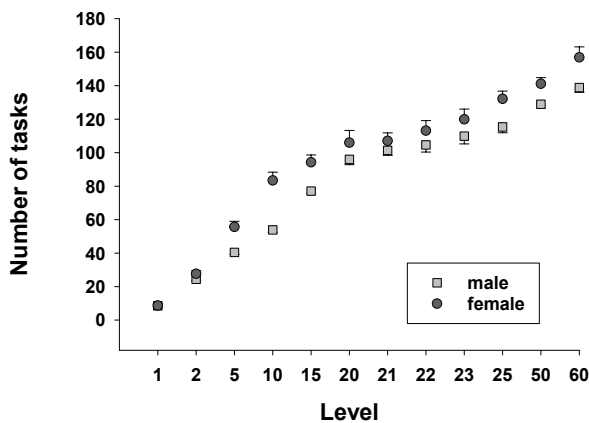

Fig. 6. Average number of tasks for each *6df* level by gender. Whiskers indicate 95% confidence interval.
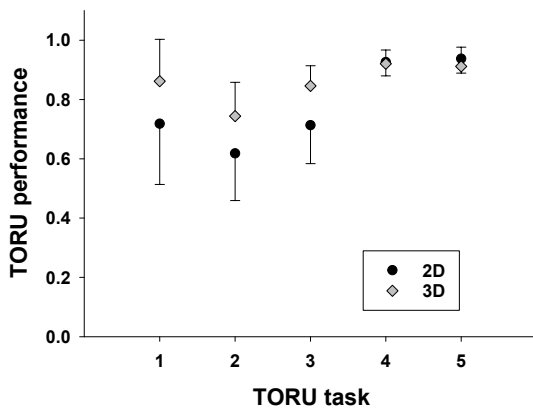

Fig. 7. Average docking performance score in the five TORU tasks for 2D and 3D group. Whiskers indicate 95% confidence interval.

outcome ($F(8, 85.18) = 8.96, p < .001$). Stereoscopic presentation, therefore, did not only have an influence on learning speed in the 6df program, but also on learning success regarding performance during the first Russian docking tasks. Nevertheless, at the end of the TORU tasks, 2D participants performed as good as the 3D group – so once again there was no persisting effect of stereoscopic presentation.

4. Discussion

We did not observe a consistent benefit of 3D presentation compared with 2D. Although 3D participants descriptively required fewer tasks on average than the 2D participants to reach each individual training program level, statistical analysis of these differences yielded equivocal results. Whereas group comparisons by Mann-Whitney tests at measuring points level 15 and 60 failed to reach significance, having a closer look at the whole learning process via LME modelling could significantly confirm a positive effect of the 3D presentation that was dependent on the difficulty level. While we observed no general advantage for participants in the 3D group, they did learn faster at least during the first portion of the course according to the mixed model. The hypothesis that stereoscopic presentation of the *6df* learning tool does facilitate the learning process compared to standard 2D can be confirmed only partly and with restrictions: 3D seems to facilitate learning; however, the effect was attenuated after switching to the standard 2D course. Gender and age both affected learning speed, with steeper learning curves in younger individuals and in men. In a previous study of Johannes et al., a similar effect of age was also present, whereas there was no significant influence of gender [4]. Experience with computer games or simulations might be a possible explanation for this (in this study, all participants who reported being passionate video game players were male and in the younger age group). Video gaming could have an impact as it has been associated with improvements in spatial abilities, as reported in a review by Spence and Feng [22]. Gaming experience occasionally also relates to performance in operational tasks, for example in a robot navigation study of Gomer and Pagano [23].

In addition to learning speed, learning success was measured as performance in a series of docking training tasks that have been used by cosmonauts in space. Although there was no general effect of the stereoscopic presentation, 3D participants outperformed 2D participants during the first three tasks. Participants in the 3D group seem to have adapted faster to the new circumstances, as TORU tasks follow different mechanics (e.g. high inertia of the spacecraft) and, therefore, require generalization of the acquired skill. We speculate that the stereoscopic group may have built up a more robust sense for their position and orientation in space. Taken together, stereoscopic presentation seems to have a positive, but rather small impact on learning to control six DoF.

Our ambiguous findings may be explained in part by the large interindividual variance in learning speed. Indeed, the number of completed tasks until the level 15 breakpoint ranged from 56 to 160. While the sample size was relatively large for a complex bed rest study, it was not sufficiently large to reduce the impact of exceptionally slow or fast learners or for detailed subgroup analysis. The latter could serve to detect predictors for individuals who are more likely to benefit from 3D presentation as training aid. Former experience or familiarization with 3D glasses or virtual reality environments for example might have an impact, as well as general computer affinity. Future studies might also account for spatial orientation ability, which could conceivably contribute to variability in performance. Wang et al. [24] discovered that perspective taking and mental rotation ability are associated with manual docking performance, which might be particularly relevant for novices, according to Du et al. [25]. 3D presentation could be more beneficial for those with limited spatial orientation beforehand, whereas skilled persons might benefit less. Despite the small sample size, bed rest provided an exceptional opportunity to investigate performance under extreme conditions that at least partly resemble the adverse conditions astronauts are facing.

Stereoscopic viewing has been associated with symptoms ranging from discomfort to motion sickness due to visual conflicts [26]. None of the participants reported adverse events when wearing 3D glasses. Still, some experienced the stereoscopic presentation as more strenuous and tiring for the eyes compared to 2D. A few participants reported difficulties integrating stereoscopic double images into one consistent three-dimensional view. These issues might have reduced the benefit of the 3D view or even hindered some participants in the learning process. Often full immersion is mentioned as an important component of VR, which can be achieved for example through head-mounted displays and creates the perception of being physically present in the virtual environment [6]. Nevertheless, there have been non-immersive approaches like in our study, using virtual 3D environments that are presented on a conventional monitor. This "desktop VR" is capable of creating at least mental or emotional immersion, as suggested by Robertson, Card and Mackinlay [27]. We decided for 3D glasses instead of a head-mounted display to reduce the risk of cybersickness, but also because participants should be able to look freely at the hand controls – especially during familiarization with their functioning. The potential advantage of immersive VR is the opportunity to blind out reality and get fully absorbed in the simulation. Whether immersive VR further improves the learning process compared to 3D deserves to be studied. Nevertheless, Aoki, Oman, Buckland and Natapoff observed that non-immersive VR is not necessarily inferior to immersive VR in navigation training contexts [14]. In reality, docking is also done in front of a 2D screen while seeing the hand controls. Therefore, immersion would require virtual imaging of hands and controls, e.g. by using wired gloves. Our main interest was to visually clarify spatial relations, which the simpler 3D glasses are sufficient for.

In conclusion, stereoscopic presentation during the acquisition of the ability to control objects with six DoF had only small effects on learning speed and success. Whilst facilitating learning during the first few sessions, this benefit did not persist throughout the course and seemed to fade away as soon as there was a switch to standard 2D. 3D training may have slightly improved the ability to accustom to varying mechanics like during TORU. In the end, however, performance in this task did not differ between groups. Nevertheless, there are some interesting starting points for further research on possible learning aids as well as on factors influencing the learning process. As manual docking in space relies on 2D screens and not all participants seem to benefit from 3D, we favor the simpler, less costly, but more realistic 2D learning program.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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