Visual Attention Relates to Operator Performance in Spacecraft Docking Training

Sarah Piechowski; Bernd Johannes; Willi Pustowalow; Michael Arz; Edwin Mulder; Jens Jordan; Oliver T. Wolf; Jörn Rittweger

BACKGROUND: Manually controlled docking of a spacecraft to a space station is an operational task that poses high demands on cognitive and perceptual functioning. Effective processing of visual information is crucial for success. Eye tracking can reveal the operator's attentional focus unobtrusively and objectively. Therefore, our aim was to test the feasibility of eye tracking during a simulation of manual docking and to identify links between visual information processing and performance.

METHODS: We hypothesized that duration and number of gazes to specific regions of interest of the simulation (total dwell time and number of dwells) would be associated with docking accuracy. Eye movements were recorded in 10 subjects (30% women, $M = 33.4$ yr old) during the 6° head-down tilt bed rest study AGBRESA during 20 training sessions with the 6df learning program for spacecraft docking.

RESULTS: Subjects' gaze was directed most frequently and longest to the vizor (185 dwells and 22,355 ms per task) followed by the two instrument displays (together 75 dwells and 4048 ms per task). We observed a significant positive relationship between number and duration of visual checks of speed and distance to the docking point and the accuracy of the docking maneuver.

DISCUSSION: In conclusion, eye tracking provides valuable information related to docking accuracy that might prospectively offer the opportunity to improve docking training effectiveness.

KEYWORDS: manually controlled docking, eye tracking, operator performance.

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Manually controlled spacecraft docking to a space station is a highly safety-relevant maneuver.[3,9] Docking success depends on the ability to control objects with 6 degrees of freedom (DoF). A spacecraft can be navigated along three translational axes and rotated around each axis, which poses substantial challenges to cognitive functioning, motor control, and visual attention. The 6df training tool has been introduced to help the operator acquire and maintain the skill to control 6 DoF autonomously.[16,17] Software was developed by SpaceBit GmbH (Eberswalde, Germany) and hand controls by Koralewski Industrie-Elektronik oHG (Hambuehren, Germany) as a research tool for the German Aerospace Center (DLR) to investigate operational performance based on the Russian TORU manual docking platform. To further improve learning effectiveness and docking reliability, additional information about the underlying information processing would be beneficial.

Given its unobtrusive nature and tight link to cognitive processes, eye tracking is particularly promising in this regard. The observer usually focuses attention at the central direction of gaze, which can be followed through eye tracking.[8,19] Metrics like the number and duration of fixations or dwells are, therefore, used as objective indicators of visual attention.[14] In aviation, eye tracking is an established method to investigate visual

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information acquisition in the cockpit and train pilots to adhere to optimal scanning patterns.[35] It has been used to detect states of high workload and fatigue[26] or to differentiate between novices and experts.[2] For example, expert pilots show shorter dwells, but more frequent instrument checks than novices,[2,10] suggesting differences in the efficiency of information processing. Also, eye tracking metrics are indicators of situation awareness and useful to determine whether situational changes in the cockpit are actually identified.[31,34] Attention allocation plays an important role for situation awareness, which is predictive of piloting errors.[33] Piloting performance has been associated with more systematic and selective instrument scanning behavior and such successful strategies can be used to improve instructions during training.[4,12,20]

While some eye tracking devices had been developed especially for spaceflight,[5,6] none of them are currently being used in space. Current, state-of-the-art eye trackers are easier to apply and not as bulky as former devices, which makes them attractive for utilization in space. The identification of effective visual scanning behavior during docking might enhance man-machine interaction. However, there are only a few studies of eye tracking during simulated spacecraft docking, aiming at the differentiation between novices and experts[15] and the prediction of performance based on scanning paths.[25] Another research question has been the assessment of an operator's mental workload, fatigue, and attention allocation via eye tracking.[30] As Huemer et al.[15] stated, little is known about information acquisition strategies in spacecraft cockpits and extrapolation from studies of aircraft environments can be problematic, as task requirements differ substantially. Just as in aviation, accuracy and safety of a docking maneuver might be further improved through more efficient training based on optimizing visual scanning profiles. Eye tracking might also facilitate the prediction of operator performance and reliability.

The purpose of this study was to examine whether the analysis of eye movements during 6df docking training provides additional information regarding key factors that contribute to operator performance. Head-down bed rest studies provide a consistent and controlled space analog environment,[11] which allowed collecting feasibility data of eye movements during docking training. As one may infer visual attention allocation from fixations, we expected that certain measurable characteristics of visual fixation are linked to docking performance. This study was performed to identify such indicator characteristics in the context of the 6df tool. Specifically, we explored the relationship between the duration (total dwell time) and frequency (number of dwells) of visual attention to predefined regions of interest (ROI) with the accuracy score of the docking maneuver.

METHODS

Subjects. Subjects were part of the Artificial Gravity Bed Rest Study with the European Space Agency (AGBRESA), which took place in the :envihab facility of the Institute of Aerospace Medicine at the German Aerospace Center (DLR) in Cologne, Germany. After 15 d of familiarization and baseline measurements, subjects spent 60 d in 6° head-down tilt bed rest to simulate the effects of microgravity. After the bed rest phase, subjects stayed in the facility for a 14-d in-house follow-up in order to monitor and facilitate rehabilitation. Our substudy consisted of a training course on how to maneuver an object with 6 DoF using the 6df tool. Because half of the subjects were allocated to a stereoscopic version of the 6df tool that was tested as a learning aid,[27] we were able to collect eye tracking data from 12 of the 24 subjects in two study campaigns. Two subjects had to be excluded due to an insufficient amount of eye tracking data, leading to a final sample of 10 healthy subjects with normal or corrected-to-normal vision. Only glasses were allowed for vision correction. Exclusion criteria involved increased intraocular pressure, acuity correction via laser eye surgery, astigmatism (>3 dpt), myopia (>−6 dpt), hyperopia (>+5 dpt), color vision deficiency, or any other condition with substantial influence on vision. The three women and seven men were 23 to 54 yr old ($M = 33.40$, $SD = 9.01$). Subjects provided written informed consent and were granted monetary compensation for taking part in AGBRESA. The study was prospectively registered with the German register for clinical studies (www.drks.de) with the identifier DRKS00015677 and approved by the ethics committee of the medical association of North-Rhine in Duesseldorf, Germany.

Equipment. The 6df training tool has been described in detail in previous publications.[16,17] In short, 6df is a computer-based and self-sufficient learning program that simulates manual control of an object with 6 DoF or, more specifically, manual spacecraft docking to an abstract space object. Subjects are gradually instructed to control up to 6 DoF. Each task starts with an illustrated instruction text, sometimes including explanatory videos. After each task, performance feedback is given. This includes docking speed as well as yaw, pitch, and bank angles between spacecraft and space station. Based on safety ranges, these parameters are each transformed into a score ranging between zero and one. This performance rating resembles the Russian TORU docking system and is explained in detail by Johannes et al.[18] As an overall docking accuracy score we used the lowest parameter score, because the largest deviation from perfect alignment determines docking success, even if all other parameters should be satisfactory. In this study, all analyses are based on this overall docking accuracy score. A docking accuracy of 0.85 or higher resembles a sufficient performance (docking possible) and a score of 0.95 good (desirable) performance. A docking accuracy lower than 0.85 indicates that the docking maneuver failed. The 6df program adapts to the individual learning speed: if the operator achieves a docking accuracy of at least 0.95, the next (more difficult) task of the training program is presented. An accuracy between 0.85 and 0.95 leads to the repetition of the same task. If the score is below 0.85, not only the actual task has to be repeated, but also the one before. Twelve levels of ascending difficulty are included, which are labeled 1, 2, 5, 10, 15, 20, 21, 22, 23, 25, 50, and 60. Levels 1 (1 DoF) and 2 (2 DoF) familiarize the trainee with each hand control individually. Levels 5 and 10 introduce a predefined flight path (guiding rings) and trainees control 2 DoF, at first consecutively, then simultaneously. Finding the center line (direct line to approach the docking point from safety distance) and stabilization before starting the approach is trained in level 15. In level 20, the spacecraft is already perfectly oriented toward the station, but the trainee has to control the approach speed and first docking contact. Levels 21, 22, and 23 include a linear flight to the center line (flight path is indicated via guiding rings), stabilization, approach, and docking. The number of necessary maneuvers to achieve perfect orientation is increased stepwise. Level 25 is similar, but guiding rings are omitted and subjects have to maintain the proper flight path on their own. For levels 50 and 60 a full standard docking maneuver is required, which is composed of a curved flight around the station to the center line, stabilization, approach, and docking. The flight path is predefined in level 50, but not in the final level 60. Each level comprises several docking tasks of similar difficulty.

Because of the bed rest design, subjects remained supine in 6° head-down tilt without a pillow during all experimental sessions. A 1366 × 768-pixel screen was fixed above the subjects' heads (parallel to the bed) at approximately 60 cm distance to display the 6df docking program. The hand controls for docking (left one for translational movements, right one for rotation) were mounted on a vertically adjustable rack above the subjects' hips so that they could be used conveniently in a lying position with elbows resting on the bed. The remote eye tracking device was attached to the lower edge of the screen. We used Tobii 4C (Tobii Technology, Danderyd, Sweden), a lightweight commercially available eye tracking gear with a binocular sampling rate of 90 Hz. The device uses near-infrared light to create a corneal reflection whose relative position to the pupil's center is measured.[8] This technique allows unobtrusive data collection without head restriction. Light conditions in the laboratory were held constant.

Procedure. Each subject completed at least 20 6df training sessions of approximately 45 min. Sessions were scheduled on average twice a week during the study course, three sessions before bed rest and the remaining sessions during the 60-d bed rest period. Sessions were minimally 1 d and maximally 7 d apart, but the usual interval was every 3 to 4 d. Each single docking task comprised up to 12 min without instructions and feedback, depending on the level (some tasks can be solved faster than others) and the spacecraft's speed (subjects have to follow a speed limit, but they are free to move slower). Therefore, the number of tasks in each session also varied. At the beginning of every session, Tobii's standard 5-point calibration was conducted. In the middle and in each corner of the black screen a red dot appeared and had to be fixated until it vanished. Subsequently, the 6df training started and subjects completed the tasks at their own pace.

Statistical Analysis. Although there are exceptions to this rule, it is generally assumed that the point of attention can be inferred from the position of a fixation.[14] During a fixation, the gaze rests relatively still at a certain point of attention for a short period of time[8] and visual information is obtained.[28,29] A temporal threshold of 100 ms is oftentimes recommended to define a single fixation.[22,23] The Tobii 4C stores 90 gaze coordinates (samples) on the screen per second. Accordingly, we defined fixations to consist of a minimum of nine subsequent gaze samples within an ROI to meet the fixation duration threshold of 100 ms. Four nonoverlapping ROI were specified on the 6df screen as shown in **Fig. 1**: task overview (depicts the task from above), vizor (pentagon that should always be aimed toward the docking cross of the station), standard instruments (speed and distance in relation to the station), and auxiliary instruments. The auxiliary instruments display gives the same information about current speed and remaining distance to the docking point, but is more salient and color-coded: if a subject is too fast or too slow, it will turn from green to yellow and eventually to red. Each ROI is a fixed zone on the screen and has been defined along the outlines of the respective 6df element (vizor, instruments, task overview). As a measure of the amount of attention that each ROI attracted, we computed total dwell times (reported in milliseconds) as the sum of the durations of all fixations recorded within each ROI per task.[14] To track how often information was retrieved from an ROI, we additionally looked at the number of dwells by counting visits to each ROI.

Data processing and statistical analyses were carried out using SPSS Statistics 21 (IBM, Armonk, NY, USA) and R 3.5.3 (The R Foundation, Vienna, Austria)/RStudio (RStudio Inc., Boston, MA, USA). All tests were two-tailed and the level of significance was set to $\alpha = 0.05$. We excluded the first five levels (1, 2, 5, 10, 15) from analysis because these tasks are for familiarization with 6 DoF and did not involve final approach and docking contact. Additionally, tasks that ended early due to collision with guiding rings that mark the ideal flight path were excluded. Hence, visual task structure and the docking accuracy score of all remaining tasks were comparable. Outlier tasks with a docking performance more than two standard deviations below the mean docking accuracy score of all subjects (<0.95) were dropped. Because subjects already received some training in earlier levels and the task difficulty increases throughout the learning program, completely insufficient performance was rare and mostly associated with ring collisions. For a safety relevant operational task like docking, even small differences within the upper bandwidth of performance are crucial. Possible relationships were sought between dwell times and numbers of dwells within the defined ROIs and the 6df docking accuracy score. We computed linear mixed-effects models (LME) with docking accuracy as a dependent variable, a random intercept for subjects, and as fixed factor dwell times on each ROI and number of dwells to each ROI, respectively. Variance components was chosen as covariance structure. Residuals could be accepted as sufficiently normally distributed by inspection of Q-Q plots and histograms.

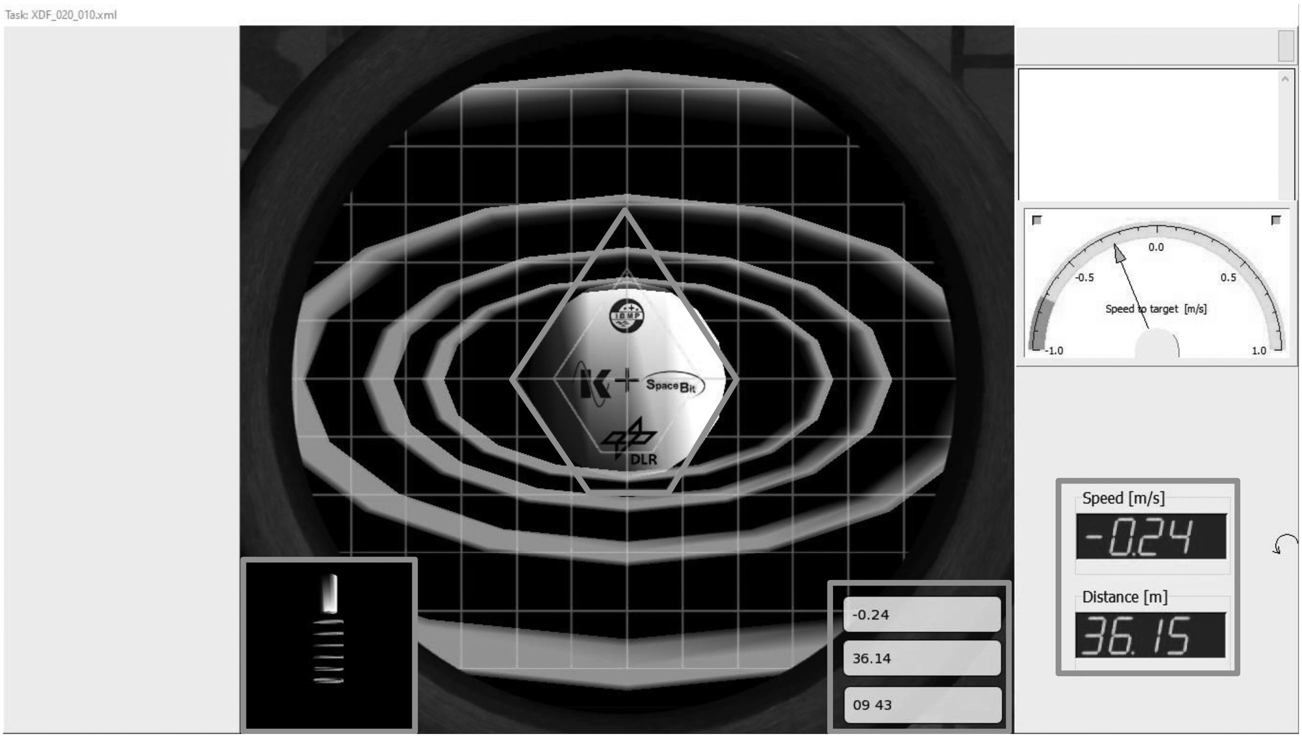

Fig. 1. Docking task with four ROI outlined: task overview (bottom left, sized 3.5% of the screen), vizor (central pentagon, 6.6%), standard instruments (bottom center right, 3.2%), and auxiliary instruments (bottom right, 4.8%).

RESULTS

Taken together, subjects completed 493 docking tasks with eye tracking, with 412 meeting our inclusion criteria. As depicted in **Fig. 2A**, comparing the four ROI, most of the total dwell time per task was dedicated to the vizor (M = 22,355.09 ms, SD = 9018.27). There was one exception for level 20, which is the first introduction to actual docking contact. In level 20, the spacecraft was already centered in front of the station and, therefore, only docking speed had to be controlled. Task overview (M = 128.09 ms, SD = 160.87) and standard instruments (M = 724.59 ms, SD = 1293.99) were rarely attended. The auxiliary instruments display instead attracted substantial total dwell time (M = 3323.24 ms, SD = 1902.50). The number of dwells during each task followed a similar pattern (**Fig. 2B**): subjects most often visited the vizor ROI (M = 185.20, SD = 115.85), but barely the task overview picture (M = 6.53, SD = 7.61). Also, they looked more often to the auxiliary instruments (M = 50.53, SD = 26.01) than to the standard instruments (M = 23.54, SD = 25.57).

Looking at docking performance, we observed a significant effect of dwell time on standard instruments [$F(1, 317.82) = 4.66$, $P = 0.03$] as well as on auxiliary instruments [$F(1, 395.17) = 14.05$, $P < 0.001$] on the accuracy score. The more

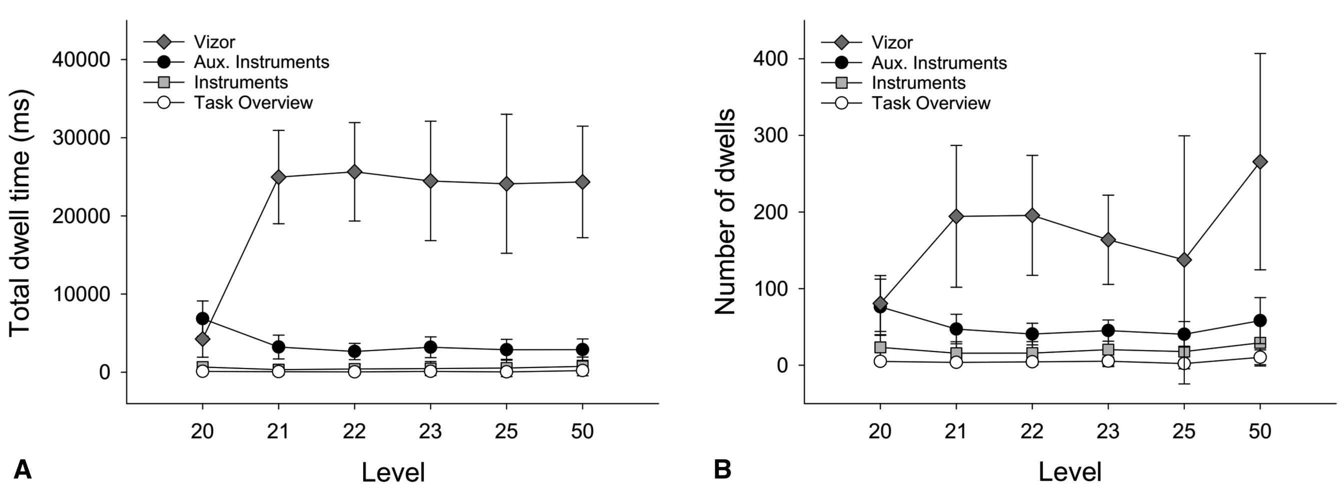

Fig. 2. A) Mean total dwell time and B) mean number of dwells per task on defined ROIs by levels of the training program. Error bars indicate the standard deviation.

dwell time subjects directed to information about actual speed and distance, the higher was their docking accuracy in the learning program. Dwell time on task overview had no significant impact on docking performance [$F(1, 226.04) = 0.42$, $P = 0.52$]. Dwell time on the vizor was significantly negatively related to docking accuracy [$F(1, 407.21) = 5.61$, $P = 0.02$]. We suspected this effect to be caused mainly by level 20, where subjects only had to control approach speed and barely observed the vizor. Indeed, when level 20 was omitted and the analysis repeated, the effect of vizor dwell time on accuracy had a positive direction, but was not significant any more [$F(1, 283.89) = 3.59$, $P = 0.06$]. Considering the number of dwells rather than the amount of time each ROI was observed, docking accuracy was significantly higher the more frequently subjects looked at the auxiliary instruments [$F(1, 372.45) = 8.26$, $P < 0.01$]. We did not observe significant effects of number of dwells on standard instruments [$F(1, 271.68) = 1.98$, $P = 0.16$], vizor [$F(1, 406.85) = 0.29$, $P = 0.59$], or task overview [$F(1, 226.52) = 2.28$, $P = 0.13$].

DISCUSSION

We collected eye tracking data during 6df docking training in a space mission analog environment to explore if visual attention provides additional information about operator performance. Eye tracking technology, which is already appreciated in the aviation domain,[26,35] proved to be feasible and unobtrusive in the spacecraft docking context of our study. In airplane cockpits, areas that are critically important for a given task, or areas that frequently change, attract the most total dwell time.[10] Similarly, during 6df docking, as the vizor's cross should always be directed at the docking point, subjects focused their visual attention mostly on the vizor, and therefore on the space station. This observation is consistent with findings of Tian and colleagues,[30] who reported that about 80% of their subjects' fixation times were directed toward the space station and about 20% to numerical displays. Subjects substantially favored auxiliary instruments over the standard ones, which indicates that learners were making use of the additional information given about actual and required speed. The task overview was generally rarely attended and probably deemed to be expendable.

Subjects who devoted more total dwell time to both instrument displays achieved higher docking accuracy scores. Also, a higher number of dwells to the auxiliary instruments was related to better performance. Frequently and thoroughly checking the concordance of speed and remaining distance seems to be essential for successful docking. In this context, the capability of swiftly detecting deviations from optimal speed might point to differences in situation awareness. This relates to previous literature that emphasizes high situation awareness based on visual attention as an important safety factor in aviation.[31,33,34] Docking accuracy was not related to total dwell time or number of dwells regarding the task overview. This ROI was in general rarely observed by the subjects. The number of dwells to the vizor had no effect on performance; however, total dwell time on the vizor was negatively associated with docking accuracy. The association was explained by level 20, which only demands controlling approach speed. While most of the dwell time and frequency was devoted to the vizor, this was not significantly related to docking accuracy.

Although successful task completion obviously required much dwell time and many dwells on the vizor, gazes to the instruments were the best indicator of performance. Our analyses regarding level 20 even indicate that spending too much time on the station (presumably at the expense of retrieving instrument information) could even hamper performance in some instances. This might be in line with previous observations that experts had better defined scan patterns and concentrated more on the most important instruments.[4,20] Importantly, duration and frequency of visual attention to the instruments were positively related to docking performance. Studies in the aviation domain have frequently linked gaze behavior to piloting performance[4,20,35] and our results confirm the potential of eye movement analysis for spacecraft docking.

Further studies are needed to investigate if—and to what extent—eye tracking data as total dwell time and number of dwells can actually explain performance and predict operator reliability. As a next step, these results could also be useful to improve the 6df learning program, for example, by providing tailored eye tracking-based feedback to remind the trainee to regularly check the instruments during training. This could be implemented with a replay of the docking task that incorporates the operator's scan path over time. In the Soyuz environment as well, instrument information is placed at the margins of the screen. Therefore, if one focuses the vizor at the station, attention must be redirected actively to the instruments. To establish an instrument-checking routine, the display could flash if it is not regarded by the trainee. Understanding how scanning behavior differs between novices and experts would be interesting, as learners could be alerted when their strategy deviates from an optimal expert scan pattern.[15,25] Our study did not include experts, but studies in aircraft cockpits suggest systematic differences from novices in duration and frequency of dwells.[2,10,20] Optimal gaze behavior in a spacecraft could include allocating much attention to the instruments by checking them frequently. However, experts might be able to process information more effectively and therefore have shorter dwells.

Which among the growing number of eye tracking-derived measures are most appropriate for a certain research question is still controversial.[21] In an aviation context, total dwell time and number of dwells have been frequently used to assess visual attention allocation.[10] We aimed at collecting feasibility data to explore the benefit of eye tracking during docking training; therefore, we chose these standard measures. Next, the features of optimal gaze behavior could be analyzed in more detail, e.g., by assessing transition patterns or single fixation durations. Analysis of scanning entropy would allow for the evaluation of performance effectiveness. Unfortunately, the low sampling rate of the Tobii 4C did not allow for the computation of saccadic metrics. Eye tracking has also been used as an indicator for workload,[1,24,26] which is interesting especially for operational tasks, because high workload can facilitate performance decrements and human error.[7,32] But unlike Tian et al.,[30] we were not able to identify pupil dilation as useful to monitor mental workload in the context of docking. Pupil dilation is very sensitive to even small differences in lighting conditions, but in the operational context of docking, sufficient control of the screen as well as environmental brightness and contrasts seemed unrealistic. Because our results were strongly biased by screen luminosity, we did not report pupillometry results for this study and suppose that a more robust eye tracking-based measure might be more promising for the future. A limitation of the eye tracking device used in this study is the lack of verified information on its accuracy and precision. However, Hild et al.[13] evaluated the accuracy of the device in 12 subjects, resulting in a satisfactory accuracy of 0.96° of visual angle. Apart from these methodological considerations, there are significant advantages of using eye tracking to examine the operator's information processing. Eye tracking devices are relatively inexpensive, lightweight, and easy to use. Attention can be assessed objectively and continuously. Importantly, data acquisition is unobtrusive and does not interrupt the operator, which is crucial for the implementation in operational tasks. A limitation of this study, however, is the small sample size. Despite this limitation, eye tracking proved suitable in examining information processing during docking training and deserves to be tested in larger samples.

We conclude that sampling with a small commercial eye tracking device provided valuable insight into information processing during docking with the 6df learning program.[16,17] Visual attention was related to performance in a simulated manual docking maneuver. Specifically, frequency and duration of processing speed and distance information were both associated with higher docking accuracy. Our results are a first step to identify eye-based indicators that can possibly be employed to assess interindividual differences in skill, but also intraindividual fluctuations in manual docking performance. Additionally, performance-associated scanning behavior could contribute to the improvement of docking training, for example, by giving trainees tailored feedback. This might be especially promising for future long duration missions, which require autonomous performance monitoring and training of operational skills.

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