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Effect of Time-delay on Lunar Sampling Tele-Operations: Evidences from Cardiac, Ocular and Behavioral Measures

Shahrzad Timman^{1,2,*}, Markus Landgraf¹, Christoph Haskamp³, Stephanie Lizy-Destrez², Frederic Dehais²

Abstract

The purpose of this study is to quantify performance in human-robot interaction under time-delay conditions in a lunar tele-operations sampling task, by testing the hypothesis that an increase of time-delay would lead to higher perceived workload and lower human performance in human-robotic integrated operations. Tele-operation is key in the exploration of the Moon, and allows for robotic elements to be controlled from orbital infrastructure and other planetary bodies such as the Earth. Considering that future missions aim to control rovers (amongst others for sampling tasks) from Earth (delay: 3s), the Gateway (delay: 0.5s) and the Moon (delay: 0s), control under the time-delay conditions for these locations must be studied. Time-delay can affect performance, and understanding the performance means that mission operations can be planned bottom-up, which benefits both the preparation of the crew and the design of rovers. An experiment was conducted with 18 engineers who were assigned to control a robotic arm under three time-delay conditions, representing the three control locations. Several metrics were derived from cardiac, ocular, subjective and behavioral measures. The analyses disclosed that the large time-delay condition statistically increased the perceived workload, the time to complete the mission and decreased heart rate variability compared to the other conditions. However, no effect of time-delay was found on attentional and executive abilities. The metrics proved to be effective in the study of performance quantification in human-robot interaction for tele-operations in lunar control scenarios. This approach can be implemented for a larger range of robotic activities, such as tele-operated driving.

Keywords: Space Exploration, Human-Robotic Interaction, Lunar Operations, Human Performance, Sampling Operations, Eye-Tracking, ECG, Human Factors

1. Introduction

Sampling on the Moon has been conducted by the Russians in three robotic missions in the Luna program, and by the Americans during six crewed Apollo missions that landed on the surface of the Moon. Today, Europe has plans of going to the Moon with robotic missions which land a rover on the lunar surface and aim to complete sample-return missions. Tele-operation is a control method that is being studied, because it allows for robotic systems to be controlled from Earth during the times that no crew is present on the Moon, and to cover the areas which are not accessible for astronauts due to human safety regulations and operations constraints.

Tele-operations allow for the interaction of the human and the robotic system, known as human-robot interaction.

This study focuses on sampling tele-operations, based on the operations of the ESA-led HERACLES mission (Landgraf et al., 2015) in which a rover is foreseen to drive on the lunar surface and perform sampling operations. The aim of the experiment is to study the HERACLES surface operations in terms of analogue tests, in order to prepare efficient operations for future crew serving in lunar missions. The sampling operations as foreseen in the HERACLES mission include scooping and picking up samples and storage in a sample container. This will be done by a robotic arm which will be positioned on a lunar rover. These mission operations are simulated in this experiment as far possible.

These space operations raise the question on how experiments between space and ground performed under the time-delay, which is a result of the distance

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of the International Space Station, ISS, can be used to assess human performance in robotic operations (Hosseini (Timman), 2016). Time-delay is a key factor in tele-operations between Earth and the Moon, and hence this study focuses on the different time-delay conditions that are true for the different lunar control scenarios, presented in this paper. Time-delay in the control sequence may cause undesired impact on performance, as presented in a study (Chen et al., 2007). This entails that there is a delay between the time in which a command is given to the system, the time this is received by the system, and the time after which the desired action is completed. In situations such as a driving rover on the surface of the Moon, a time-delay in the order of seconds can already result in dangerous situations such as loss of system in the worst case. time-delay has an effect on the performance of the operator, both in terms of motor control (Stanney et al., 1998; Kolasinski, 1995) and cognition (Yang and Dorneich, 2017; Luck et al., 2006), and therefore must be understood very thoroughly before future missions take place in which lunar rovers are deployed.

The introduction of cardiac and ocular measures has proven to be an effective method for performance assessment in the interaction between human and robotic systems (Dehais et al., 2020b). Studies (Larsen et al., 2008; Cacioppo, 2007; Coles, 1986; Stern, 2001) show that the interrelationships between the mind and the body, which is known as psychophysiology, provide much information about this performance, and show that psychophysiology involves the use of physiological signals to understand cognitive processes and human performance. One approach to derive the cognitive performance is to measure eye movements. For instance eye-tracking allows to measure the point of gaze at a given time, and the sequence in which the eyes are shifting from one place to another, as described by multiple studies (Poole and Ball, 2006; Holmqvist et al., 2011). This technique have been shown to be particularly relevant for assessing workload and performance during space tele-robotic training (Guo et al., 2021). Alternatively some studies have disclosed that the analysis of cardiovascular activity can provide added information about human-machine interactions and cognitive activity (Causse et al., 2012; Causse et al., 2009; Foy and Chapman, 2018; Charles and Nixon, 2019). For instance, another study (Dehais et al., 2011b) shows that more complex interactions with robot can lead to increased heart rate (HR). The heart rate and heart rate variability are metrics that are studied to understand the cardiac activity, using Electrocardiogram, ECG. Furthermore, studies on robotic control under time-

delay (Fong, 2001; Hambuchen, 2006; Burrige and Hambuchen, 2009; Niemeyer and Slotine, 2004) have performed experiments in which participants control robotic systems under time-delay conditions, and using planning techniques and technological tools, such as virtual tools, they aim to improve the control performance. Moreover, the working memory is an important source of information in the frame of this study, because during tele-operations between space and ground the operator will have to pay attention to instructions by ground controllers, in parallel to performing strenuous tasks.

With this knowledge, this study aims to enable the performance quantification of human-robotic interaction in tele-operated sampling task, with the use of eye-tracking and ECG for ocular and cardiac activities, respectively. This quantification must be studied for prediction and preparation of these future operations. As part of this study, an experiment, as described below, was conducted at Airbus Defence and Space in Bremen, Germany. A robotic arm was tele-operated to pick up a small shaft and navigate it to its station where it can be clicked in place. This was tested in three different time-delay conditions, to study the different control options within the Moon missions proposed by the European Space Agency.

The hypothesis of this experimental study is that an increase of time-delay would lead to higher perceived workload and lower human performance in human-robotic integrated operations.

2. Materials and methods

2.1. Participants

For this study, 18 healthy participants (mean age = 29.62 years, $SD = 2.43$, 14 male and 4 females), all staff at the German Airbus Defence and Space in Bremen were recruited by local advertisement. The subjects are all engineers with a MSc. degree working at the company in different departments. None of the participants have expertise in robotics or space operations. Participants gave their informed consent upon being informed about the nature of the experiment.

2.2. Materials

The robotic arm is the KUKA LBR iiwa 14 R820 that has seven joints and six degrees of freedom. The maximum load is 14 kg and it has a working area of 820 mm. The arm was positioned on a platform with a fixed mounting, with the freedom to move in three dimensions within the constraints of its mounting. A

fixed camera was placed such that it was aimed at the robotic arm mounting.

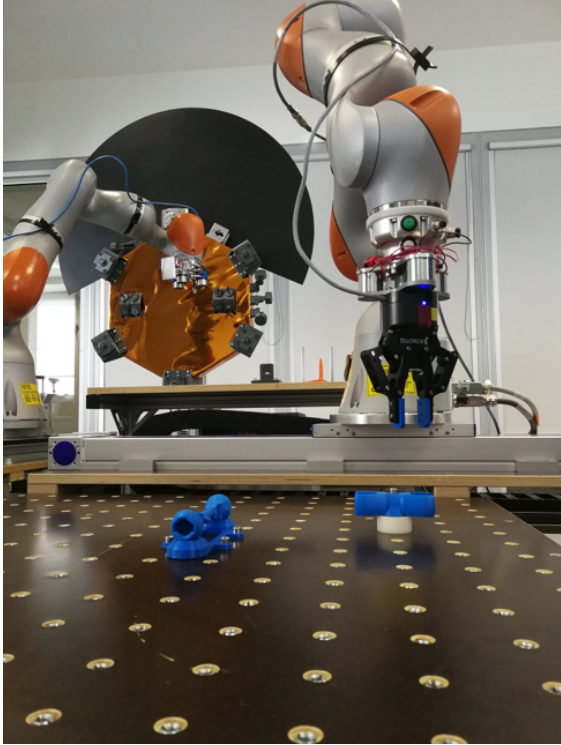


Figure 1: Robotic arm

The control station to operate the robot was placed on a closed room with no direct visual contact on the robotic arm. It was composed of the user interface, positioned at eye-height, that displays the camera video footage with an *overview* (right half) of the screen and the *close-up* (the left half of the screen) - see figure 2. The robotic arm was controlled via a joystick that can move forward, backward, to the left, to the right, and torque both clockwise and counter-clockwise. With the use of two buttons on the base, the robotic arm can also be moved upward and downward. This set-up is presented in figure 2.

2.3. Experimental set-up

The scenario was designed in which the volunteers had to tele-operate a robotic arm under different delay conditions. The volunteers were placed in the control station (see previous section) to assemble a 3-D printed shaft with another half-circled shape (see figure 4). The shaft was placed close to the robotic arm, on a small mounting which was fixed on a platform. This shaft was not fixed, but simply rests on its mounting. The other



Figure 2: Experiment set-up

element, the 3-d printed half-circled form, was placed at a small distance from the shaft. The purpose was to click the shaft in this element. Concretely, the arm had to be controlled towards the shaft, after which it had to lower and pick up the shaft. After this, the arm had to be moved towards the half-circle which was its end-position, and click the shaft in the half-circle. The logical sequence of these operations is visualized in figure 4 for clarity.

This manipulation task was repeated under three time-delay conditions, which represent different control conditions for future missions between the operator and the rover driving on the Moon. These time-delay conditions are visualized in figure 5, in which the rover, carrying the robotic arm, is sent to the surface of the Moon and operates there while communicating to the Gateway in a cis-lunar orbit. The conditions are described as follows.

- C1: 0s delay, representing the delay condition in which the controller is on the lunar surface
- C2: 0.5s delay, representing the delay condition in which the controller is on a cis-lunar station called the Gateway (at approximately 60.000km distance from the operating site)



Figure 3: Joystick interface

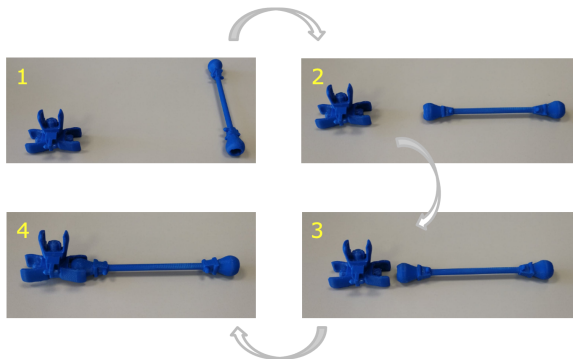


Figure 4: Visualization of the task

- C3: 3s delay, representing the delay condition in which the controller is on Earth in a control room

Along with the manipulation task, the participants had to perform a secondary working memory task that consists of memorizing different auditory seven-digit codes (eg "5-3-1-8-2-9-0") and reading them back. A total of three seven-digit codes were aurally presented when the volunteer:

- was moving the robotic arm towards the place where it must collect the shaft;

- was lowering the arm to collect the shaft;
- was about to click the shaft into its final destination.

2.4. Procedure

The participants were welcomed to the experimental facility and a small briefing was given to explain the general objective of the experiment. The subjects were trained to operate the robot and allowed them to practice and to try out the control of the robotic arm in all three time-delay conditions. The exercise started with a training period of 10 minutes. This duration of this training time was concluded in a previous study (Hosseini (Timman), 2017) that served as a pilot study for the current study and was held in preparation for this experiment. Here, the time performance results showed a converging behavior after approximately 10 minutes of familiarization with the system. When the training was completed, the Tobii eye tracker was placed over the participants and the calibration procedure was performed.

The experiment *per se* was then started and the participants had to perform the primary task (tele-operation of the robotic arm) and the secondary working memory task in the three delay conditions (C1, C2 and C3). The order of the experimental conditions was counter-balanced to control for potential fatigue or learning effects.

2.5. Measurements

2.5.1. Primary and secondary task performance

We measured the time of completion, in each of the three delay conditions, to achieve the primary task. It corresponded to the duration from the first action on the robotic arm until the arm clicked the shaft in its end position. We computed the mean number of digits that were erroneously read back by the volunteers in each of the three delay conditions.

2.5.2. Subjective measurement

The participants had to fill in the analog NASA TLX scale to report their level of mental workload after the achievement each of the three experimental conditions.

2.5.3. Eye tracking

We used the Tobii glasses eye-tracking system (100Hz, 0.5 degree accuracy) to collect participants' eye movements during task completion. Data analysis was performed using the Tobii Pro Lab software. The participants' fixations were firstly mapped on an image of reference, chosen for each participant so that it contained

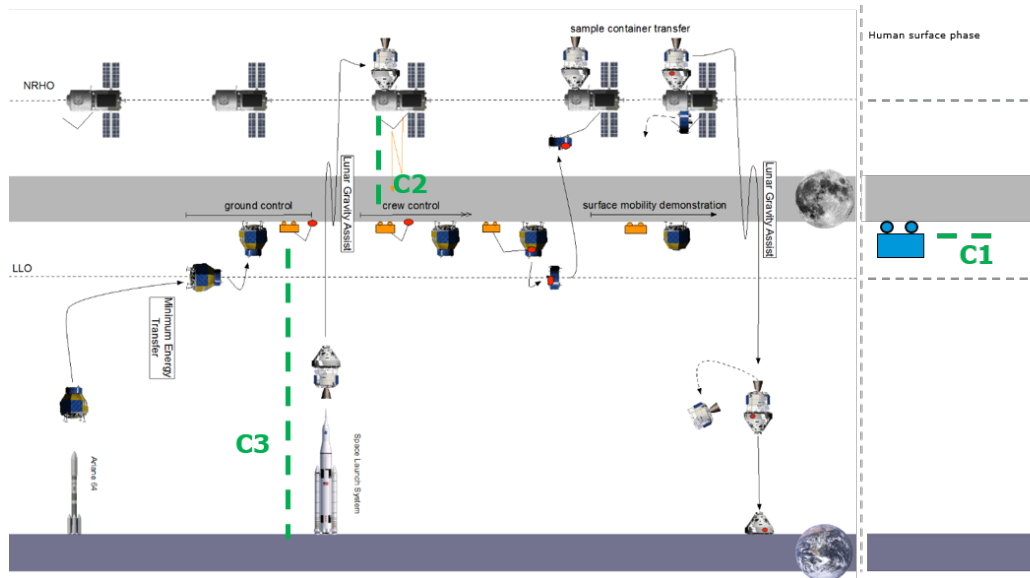


Figure 5: Time-delay overview of the HERACLES mission

the 2 Areas Of interest that were the *overview* and the *close-up*, i.e. the right half of the screen and the left half of the screen (see figure 2). We then computed the mean number of fixations per minute (fixation rate) on each of the two areas of interest, AOIs, for each experimental condition.

2.5.4. Electrocardiogram

Cardiac activity was acquired with the Faros ECG (500 Hz). The three electrodes were positioned on the right clavicle, the left clavicle, and a third electrode underneath the heart and a conductor gel was used to enhance signal quality. We then derived the heart rate (HR) and the standard deviation of the NN interval (SDNN) to account for heart rate variability (HRV). This latter metrics was computed as the standard deviation of the RR intervals of the cardiac signal.

3. Results

All statistical analyses were carried out with R-studio (1.1.423). Repeated measures of Analysis of variance (ANOVAs), were computed over the NASA TLX scores, time of completion, number and ocular metrics separately. The Tukey's honestly significant difference (HSD) test was used for all post hoc comparisons. Cardiac measures (i.e. HR and HRV/SDNN) did not follow a normal law. We then performed Friedman ANOVA and used Wilcoxon Signed Rank test for post-hoc analy-

ses with Bonferroni method to correct for multiple comparisons.

3.1. NASA TLX

A repeated measure ANOVA with time delay as repeated measure revealed significant effect of the different time-delay conditions over the total workload index: $F(1,34) = 9.13, p < .001, \eta^2 = 0.09$. Post-hoc analyses only disclosed significant differences between C1 and C3 ($p = .02$).

3.2. Time of completion (TOC)

The repeated measure ANOVA with time delay as repeated measure disclosed that the three delay conditions induced significant effect over the TOC $F(1,34) = 47.7, p = .01, \eta^2 = 0.49$. Post-hoc analyses revealed that significant differences between C1 and C3 ($p = .001$), and between C2 and C3 ($p = .001$).

3.3. Working memory

Participants committed on average 1.3 errors in C1 ($SD = 1.1$), 1.5 errors in C2 ($SD = 0.9$) and 1.1 errors in C3 ($SD = 1.0$). A repeated measure ANOVA with time delay as repeated measure revealed no significant effect of the different time-delay conditions over the number of errors in the working memory task: $F(1,34) = 2.0, p = .15, \eta^2 = 0.03$.

3.4. ECG

A first non-parametric Friedman ANOVA was conducted to assess the effects of the three delay conditions on HR and rendered a Chi-square value of 0.94 which was not significant ($p = .9$), thus preventing from running any further post-hoc analyses.

A second non parametric Friedman ANOVA was conducted to assess the effects of the three delay conditions on SDNN and rendered a Chi-square value of 8.44 which was significant ($p = .01$). Post-hoc analyses, using Wilcoxon Signed Rank test, disclosed significant differences between C1 (mean = 53.92) and C3 (mean = 46.33) ($p = .03$), and between C2 (mean = 55.93) and C3 ($p = .01$).

3.5. Eye-tracking results

A 2 (AOI) x 3 (Time Delay) repeated measure ANOVA disclosed a main effect of the delay conditions on the mean number of fixations rate per minute: $F(2,16) = 4.3$, $p = .02$, $ges = 0.05$. This analysis also disclosed a main effect of the AOI type on the mean number of fixations rate per minute with higher mean values for the left AOI (mean = 41.2, $SD = 18.42$) than for the right AOI (mean = 32.12, $SD = 3.51$), $F(2,16) = 5.0$, $p = .04$, $ges = 0.1$. No AOI x Time Delay interactions were found ($p = .4$) thus preventing us to run any post-hoc analyses.

4. Discussion

The main purpose of this study was to investigate the effect of time-delay condition on human performance for future space operation purpose. **To meet this goal, we designed a simplified tele-operation task with a robotic arm under three time-delay conditions that were similar to the ones that operators will be likely to face depending on their position (0s delay: C1 - "lunar surface", 0.5s delay: C2 - "Gateway" and 3s delay: C3 - "Earth").** Different subjective, behavioral, physiological and ocular metrics were collected.

Regarding the subjective measures, our participants qualitatively reported higher NASA TLX scores as time-delay conditions increased. However, the statistical analysis disclosed that only the most contrasted conditions with **0s delay (C1 - "lunar surface") and 3s delay (C3 - "Earth")** led to significant differences. NASA TLX encompasses several subjective dimensions such as physical and mental efforts and confirm previous findings indicating that time-delay heavily influenced the perceived workload (Adams

and Kaymaz-Keskinpala, 2004). The time-delay in the aforementioned study was 5s, which is considerably larger than the **0s delay (C1 - "lunar surface") and 0.5s delay (C2 - "Gateway")** conditions, yet comparable to the **3s delay condition (C3 - "Earth")** in our current study.

We then analyzed the effect of time-delay on TOC and working memory performance. Firstly, the statistical findings indicated that the condition with the highest time-delay led to significant TOC compared to the two other conditions. These results show some consistency with the subjective measures between the **0s (C1) and the 3s (C3)** delay conditions, but this metric appears to be more sensitive since it discloses some statistical differences between the **0.5s (C2) and the 3s (C3) delay conditions**. Again, these findings are in line with the results from another study (Yip et al., 2010) who reported higher TOC for increased time-delay in their tele-operation manipulation task. We did not find significant difference between **0s (C1) and 0.5s (C2)** but such a result was expected, considering the very small time difference between these two time-delay conditions.

The secondary working memory task was introduced to measure possible effect of time-delay on basic executive functioning. However, our results did not yield to significant difference across the conditions. Usually, working memory performance is known to decline when primary task difficulty increases (Gateau et al., 2018) and one could expect such phenomenon to occur during the highest delay condition. Authors from (Yang and Dorneich, 2017) also found that time-delay has a negative effect on cognition and emotion during a tele-operation task but contrary to our current study, the participants faced intermittent and variable time-delay in the control input. This absence of predictability regarding the system dynamic may be particularly confusing thus leading the participants to focus on the primary task at hand (operating the robot) and in return to neglect secondary cognitive tasks (alert detection). It is possible that the secondary task of in our current study may have not been challenging enough especially for our volunteers who were all young and highly educated in the field of engineering. Such population is known to exhibit higher executive functioning than normal population (Causse et al., 2011; Ashcraft and Krause, 2007; Durantin et al., 2016). These inclusion criteria for our participants was done on purpose so that they are close to the ones of National space agencies to select astronauts. Indeed, future astronauts, with

Table 1: Mean and standard deviation for time of completion (TOC), number of working memory errors (WM), NASA-TLX score, HR and HRV (SDNN) across the three time-delay conditions

	Time-Delay Conditions		
	C1	C2	C3
TOC (s)	207 (53)	220 (69)	352 (75)
WM (errors)	1.3 (1.1)	1.5 (0.9)	1.1 (1.0)
NASA-TLX (%)	55.78 (17.45)	62.85 (17.27)	69.54 (17.82)
HR (BPM)	79.58 (11.4)	79.56 (9.96)	79.26 (10.34)
SDNN (ms)	53.92 (12.59)	55.93 (13.21)	46.33 (8.68)

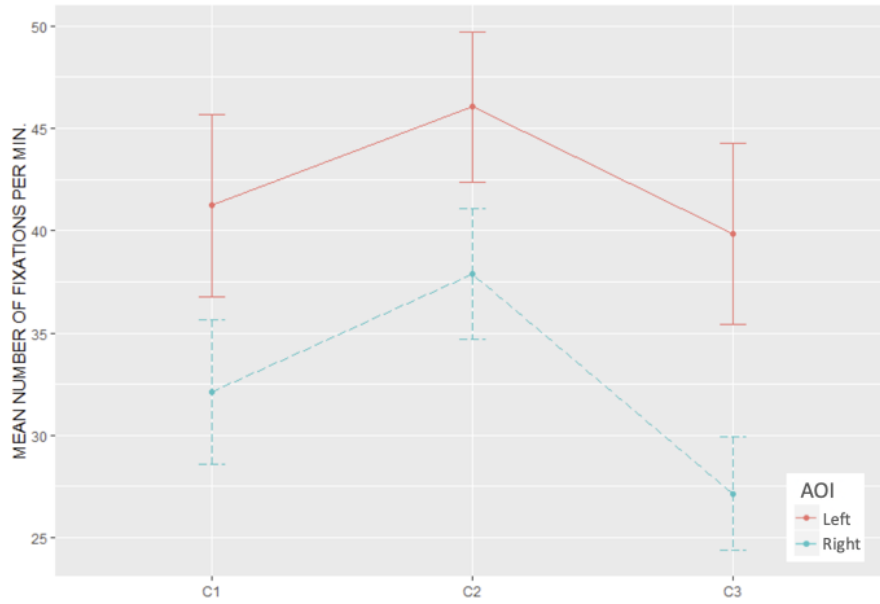


Figure 6: Mean number of fixations per minute across the three conditions for the right area of interest (in blue) and the left area of interest (in red). Bars represent standard errors.

similar background, will be sent to exploration missions and will be involved in many challenging multi-tasking assignments such as the communication with ground control and ground science teams while controlling complex robotic systems.

The analyses of the physiological data show that significant differences were found between the 0s delay (C1) and 3s delay (C3) conditions, and between the 0.5s (C2) and 3s (C3) conditions, as long as HRV (SDNN) was concerned. No statistical evidences were found regarding the HR. HR and HRV are known to account for mental effort in response to increased demand (Scannella et al., 2018; Durantin et al., 2014). However, there is still debate whether HR or HRV is most sensitive one as authors report contradictory findings (Scannella

et al., 2018). One possible explanation is that the type of task (psychomotor, cognitive), its difficulty and duration might affect these measures in different ways. However, these HRV findings are consistent with the subjective and TOC results thus supporting the hypothesis that increases in time-delay leads to higher perceived workload and lower human performance. Similar to the other metrics previously discussed, the effect was not significant between 0.5s delay (C1) and 0.5s delay (C2) conditions. This is an expected result, considering that the value of 0s delay (C1) and the 0.5s delay (C2) was selected not with the expectation that it shows performance differences, but as a representation of control conditions of the lunar surface (C1 - 0s delay) and the Gateway (C2 - 0.5s delay).

Finally, the eye-tracking results revealed that par-

ticipant's attention, as measured by the mean number of fixations per minute, was not distributed evenly on the user interface. Our participants were more focused on the left AOI (global overview) than the right one (close-up view). One could expect this result considering since the left AOI displays most of the relevant visually information, therefore requiring the most attention. A logical division of attention, which was expected in a smooth task performance in this experiment, would have been to start at the left AOI to observe the robotic arm while it is controlled to the left, then to aim for the arm to stop at the point where the shaft is located, and to move the arm down. Next, the right AOI should be used to observe the capture and rotation of the shaft in the right direction, after which the shaft must be aligned laterally with its end destination since this cannot be observed on the left AOI. After this step, the user should switch back to the left AOI to observe the approach and final fixation to the destination, with some visual alignment checks on the right AOI. This discrepancy between the expected and our participant's actual ocular behavior show that training eye movement will be of critical importance for future space operation (Ahmadi et al., 2022; Dehais et al., 2020a). Our statistical result also disclosed a main effect of time-delay on the distribution of visual of attention but the absence of interaction prevented us to conduct further analysis to identify the direction of the effect. Moreover, a visual exploration of the result did not lead to clear readability of this finding. One could expect excessive visual focus during the most difficult condition as shown by (Dehais et al., 2011a) with a 2s delay. However, our result pointing toward no remarkable effect of time-delay on attentional tunneling.

5. Conclusions

The design of future space operations remains a dynamic task, and understanding human performance is essential in the study of optimal performance in space. To that end, our study aimed at understanding the effect of time-delay on a tele-operated assembly task. We designed an ecological scenario under three representative time-delay conditions (lunar surface, gateway and Earth). Taken together, our result shown that time-delay had an impact on the time to complete the mission and workload as derived from subjective and objective metrics. However, this performance impairment does not appear to be critical as long

as attentional and executive functioning were preserved. Nonetheless, the difference between the smallest time-delay, control from the lunar surface, and the largest one, control from Earth, seems to vote in favor of human spaceflight for more efficient operations.

One limitation of our experiment is that it was performed under lab settings which lacks the stress levels of actual operations in which resources, such as time and equipment, are very costly. Indeed, future studies, experiments involving long time-delay conditions should be performed with more complex real-life multitasking scenarios (eg. radio-communication, failure management). Other factors should be manipulated such as time pressure, time-on-task and possibly sleep deprivation. If a maximum allowed completion time is introduced under fatigue, it is expected to have a deleterious impact on performance especially when time-delay is high. This is in line with real operational scenarios in which stressors often play a critical role in scheduling of operations. Furthermore, different levels of automation should be manipulated to improve human-robotic arm interactions. (Li et al., 2022)

To conclude, we believe that our ecological approach combining different subjective, behavioral and physiological measures offers a comprehensive and flexible framework to assess human tele-operation and system design for future space operations. All these measures are complementary, while being minimally invasive, and unveil different psychological, executive and attentional aspects of human performance. Such metrics could be also used for astronaut selection as well as adaptive training (Stephens et al., 2018; Wu et al., 2021). We sincerely hope that this study will encourage researchers and practitioners to adopt such an approach to design safe and efficient human-robot interaction for space operations.

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