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Impact des environnements dynamiques et de la perspective visuelle sur la performance de téléopération : du laboratoire aux situations réelles

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Abstract

Whether it's a cosmonaut operating a robotic arm on board the International Space Station, a soldier piloting a drone from a helicopter, or a teleoperator in a ground control center maneuvering a rover on the surface of Mars, the operator's primary role is to monitor and control the robot, either manually or in automatic mode. The growth of teleoperation applications leads to a diversification of environments and situations that operators may face. While teleoperation traditionally took place from a control base where the operator remained static in front of a computer, these professionals can now teleoperate from dynamic environments, such as moving vehicles. The literature shows that gravito-inertial changes a teleoperator may experience in a dynamic environment affect cognitive, perceptual, and motor performance, all crucial for teleoperation tasks. If these effects extend beyond the experimental framework and transfer to teleoperations from dynamic environments, it can be deduced that they could disrupt how the operator perceives the remote environment and the objects within it, as well as their control over the robot. This would lead to reduced operator performance, decreased user experience, and ultimately, a reduction in the usability of teleoperation systems. However, to our knowledge, the HRI community has scarcely studied the impact of the operator's body movement on the usability of teleoperation systems, and thus, beyond general recommendations, no teleoperation interface adapted to these dynamic contexts has been tested or proposed.

We address these questions in this thesis by evaluating the usability of teleoperation systems, whether simulated in virtual reality or real ones, in dynamic laboratory environments using a motion platform, as well as in more ecological contexts. The first studies conducted within this thesis focused on the effect of spatial compatibility between the operator's body orientations and those of the robot on teleoperation performance. They showed that an operator's body movement, spatially incompatible with that of the remotely controlled robot, deteriorates robot control performance. The following studies explored the effects of spatial compatibility and also proposed to examine whether a visualization interface of the remote robot could mitigate the harmful effects induced by dynamic environments. The results suggest that teleoperation in dynamic environments can reduce the usability of a teleoperation system: the dynamic environment reduces the quality of user experience (increased mental and physical demands and motion sickness), and spatially incompatible movements impact teleoperator performance. Furthermore, a third-person perspective visualization of the robot improves both teleoperators' performance and user experience. The third and final part of this thesis proposes experimental protocols to investigate whether the effects observed in the lab are transferable to more ecological contexts. Preliminary results show that in more ecological contexts, teleoperators tend to adapt to their environment in a way that preserves their teleoperation performance. However, behavioral changes, such as slowing down while controlling a real drone in a lying position, along with increased perception of physical and mental demands, and an increase in motion sickness on board a real aircraft, were observed.

Qu'il s'agisse d'un cosmonaute manipulant un bras robotique à bord de la Station spatiale internationale, d'un militaire pilotant un drone depuis un hélicoptère, ou d'un téléopérateur dans un centre de contrôle au sol manipulant un rover sur la surface martienne, le rôle principal de l'opérateur est de surveiller et de contrôler le robot, soit manuellement, soit en mode automatique. La croissance des applications de téléopération entraîne une diversification des environnements et des situations auxquelles les opérateurs peuvent être confrontés. Alors que la téléopération se faisait traditionnellement depuis une base de contrôle où l'opérateur restait statique devant un ordinateur, ces professionnels peuvent désormais téléopérer depuis des environnements dynamiques, tels que des véhicules en mouvement. La littérature montre que les changements gravito-inertiels qu'un téléopérateur peut subir dans un environnement dynamique impactent les performances cognitives, perceptives et motrices, essentielles aux tâches de téléopération. Si ces effets s'étendent au-delà du cadre expérimental et se transfèrent aux téléopérations depuis des environnements dynamiques, on peut en déduire qu'ils pourraient perturber la manière dont l'opérateur perçoit l'environnement distant et les objets qui le composent, ainsi que son contrôle du robot. Cela entraînerait une diminution des performances de l'opérateur, une baisse de l'expérience utilisateur, et, en fin de compte, une réduction de l'utilisabilité des systèmes de téléopération. Cependant, à notre connaissance la communauté HRI a très peu étudié l'impact du mouvement du corps de l'opérateur sur l'utilisabilité des systèmes de téléopération, et par conséquent, en dehors de recommandations générales, aucune interface de téléopération adaptée à ces contextes dynamiques n'a été testée ou proposée.

Nous abordons ces questions dans cette thèse en évaluant l'efficacité de systèmes de téléopération, qu'ils soient simulés en réalité virtuelle ou réels, dans des environnements dynamiques en laboratoire à l'aide d'une plateforme de mouvement ainsi que dans des contextes plus écologiques. Les premières études menées dans le cadre de cette thèse se sont concentrées sur l'effet de la compatibilité spatiale entre les directions du corps de l'opérateur et celles du robot sur les performances de téléopération. Elles montrent qu'un mouvement du corps de l'opérateur, spatialement incompatible avec celui du robot contrôlé à distance, détériore les performances de contrôle du robot. Les études suivantes explorent des effets de la compatibilité spatiale et proposent également d'examiner si une interface de visualisation du robot distant pourrait atténuer les effets néfastes induits par des environnements dynamiques. Les résultats suggèrent que la téléopération dans des environnements dynamiques peut diminuer l'utilisabilité d'un système de téléopération : l'environnement dynamique réduit la qualité de l'expérience utilisateur (augmentation des demandes mentale et physique, et du mal des transports) et les mouvements spatialement incompatibles impactent les performances des téléopérateurs. De plus, une visualisation du robot en perspective à la troisième personne améliore à la fois les performances et l'expérience utilisateur des téléopérateurs. La troisième et dernière partie de ce manuscrit propose des protocoles expérimentaux pour investiguer si les effets observés en laboratoire sont transférables à des contextes plus écologiques. Les résultats préliminaires montrent que, dans des contextes plus écologiques, les téléopérateurs tendent à s'adapter à leur environnement de manière à préserver leurs performances de téléopération. Cependant, des modifications de comportement, telles qu'un ralentissement dans le contrôle d'un vrai drone en position allongée, ainsi qu'une augmentation de la perception des demandes physique et mentale, et une augmentation du mal des transports à bord d'un avion réel, ont été observées.

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Introduction

Robotics is a rapidly expanding field, especially because of its potential in sectors like space robotics, defense, and industry. In this context, teleoperation—the remote control of robots—plays a crucial role in future exploration missions across space, military, and civil domains. Whether it's a cosmonaut operating a robotic arm from the International Space Station, a soldier piloting a drone from a helicopter, or a teleoperator maneuvering a rover on the surface of Mars, teleoperation facilitates interaction with remote and often hazardous environments while ensuring the safety of the operator.

With the rise of teleoperation applications, the environments and situations that operators face are diversifying. While traditionally performed from a static control base, where the operator sits upright in front of a computer, teleoperation is now extending to more dynamic environments, such as moving vehicles. This evolution raises new questions, particularly regarding the impact of these environments on the efficiency of teleoperation systems. However, despite the technological progress made regarding teleoperation systems, the influence of dynamic environments remains largely unexplored by the human-robot interaction (HRI) community. To date, no teleoperation interface specifically adapted to these contexts has been tested or proposed.

This thesis, funded by the French National Centre for Space Studies (CNES) and the European Space Agency (ESA), aimed to achieve two main objectives: first, to analyze the impact of dynamic environments on teleoperation; second, to evaluate the effectiveness of a visualization interface adapted to these contexts. To this end, we sought to understand how the inclination and movement of the operator's body influence their performance and experience. We also explored whether the spatial compatibility or incompatibility between the operator's movements and those of the robot has a more significant impact on user experience. Finally, we examined whether a robot visualization interface could reduce or compensate for the negative effects associated with the operator's movements. To address these questions, this research relied on a comprehensive evaluation of teleoperators' performance, behavior, and subjective experience during both simulated and real teleoperations in dynamic environments, conducted in laboratory settings and more ecological contexts. This investigation was organized into three experimental blocks. The first two blocks focused on fundamental experiments conducted under controlled laboratory conditions, using a virtual reality headset and motion platform. The final block proposed experimental protocols in environments that more accurately represented real-life teleoperation conditions.

Chapter I of this manuscript presents teleoperation, its various fields of application, and how the evaluation methods of the effectiveness of teleoperation systems that the literature proposes. It also discusses the various teleoperation challenges and proposed solutions in this field. **Chapter II** examines the impact of dynamic environments on teleoperation. After discussing the characteristics of dynamic environments and briefly explaining how humans perceive motion, this chapter reviews studies evaluating the impact of gravitational and inertial changes on the human capabilities necessary for teleoperation, as well as some

studies conducted in more operational environments. This chapter concludes with the presentation of the research objectives and the description of experimental protocols designed to fill the gaps identified in the literature on the impact of dynamic environments on teleoperation. **Chapters III, IV, and V** present the contributions of this thesis. The first studies (**Exp I.a** and **Exp I.b**), presented in **Chapter III**, focus on the effect of spatial compatibility between the operator's body orientation and that of the robot during teleoperation. They show that body movements that are spatially incompatible with the robot's degrade control of the latter. The following studies (**Exp II.a** and **Exp II.b**), presented in **Chapter VI**, explore the effects of spatial compatibility while examining whether a robot visualization interface could mitigate the negative effects induced by dynamic environments. The results suggest that teleoperation in dynamic environments can reduce the efficiency of teleoperation systems by increasing mental and physical demands, as well as motion sickness, while incompatible movements impact operators' performance. Furthermore, a third-person visualization interface improves both performance and the teleoperators' experience. Finally, **Chapter V** proposes experimental protocols to assess whether the effects observed in the lab can be transferred to more ecological contexts (**Exp III**, **Exp IV**, **Exp V**). Preliminary results show that, in more realistic contexts, teleoperators tend to adapt to their environment to preserve their performance. However, behavioral changes, such as slowing down when controlling a drone in a prone position, along with increased mental and physical demands, and intensifying motion sickness aboard a real aircraft, were observed.

This research enhances our understanding of how dynamic environments influence teleoperation and introduces innovative methods to assess teleoperation from laboratory settings to real-life applications. Additionally, it proposes recommendations regarding interface solutions for the first time, aiming to improve operator effectiveness and safety across diverse scenarios.

STATE OF THE ART

I. Teleoperation generalities

The term *robot* comes from the Czech word *robota*, which means *drudgery*. It was first used by the Czechoslovakian author Karel Čapek in 1920 in his science-fiction play *Rossum's universal robots* (Čapek and Kallinikov, 1940). In this play he tells the story of the creation of humanoid robots to whom intelligence and sensitivity were granted, eventually leading to their rebellion and the annihilation of humanity. Since then, interest in robots has grown, and the media presented robots controversially. Some portray them as a threat (such as in *The Terminator*, James Cameron 1984), while others as social companions (as seen in *Star Wars*, Georges Lucas 1977). Meanwhile, scientists were working to make this fiction a reality. In the 1950s, thanks to the encounter between the inventor George Devol and businessman Joseph Engelberger, the first robotic arms, known as Unimates #001, entered the automotive industry, relieving workers of repetitive and dangerous tasks on assembly lines. As a result of their success, these types of automates diversified and spread to various sectors worldwide.

We're still far from the science-fiction scenarios where robots take over humanity. However, robots are an integral part of our modern lives. Many industries rely on automation or collaborative robots to ensure productivity and security (Almurib et al., 2012), and social robots provide entertainment and assist with domestic tasks (Henschel et al., 2021). Another crucial application of robotics, which is at the heart of the present research work, is teleoperation (Chen et al., 2007). While ensuring the safety of operators, telepresence and teleoperation, made possible by the remote control of robots, increase human capacities for perception and action in remote environments. Robotic technologies such as cameras, radars, and other sensors enable operators to perceive further and more accurately, in different frequency bands for instance, than their human senses. Remote robots can perform complex tasks, operate for extended periods, and withstand extreme conditions such as oxygen-deprived environments, toxic atmospheres, and extreme temperatures and pressures, as may be the case in undersea or space environments. Therefore, teleoperation systems can offer effective solutions in multiple application domains, ranging from enabling remote presence in meetings, industrial robotics, medicine, and military to space exploration.

After introducing teleoperation in the broader context of human-robot interaction, this first chapter offers an insight into the definition, origins, and evolution of teleoperation in robotics, and presents the various application domains it covers today. How to asses teleoperaiton system efficiency as well as teleoperaiton challenges and solutions.

1 | Defining teleoperation: principles and evolution

1.1 | Human-robot interaction and teleoperation

Human-robot interaction (HRI) involves a close interaction between the human operator and the robot. The HRI field of research studies the quality of this interaction in tasks requiring human-robot teaming. Its objective is to consider the human during the design of user interfaces, ensuring interactions are not only safe but also intuitive, efficient, and comfortable. HRI can be divided into four application domains (Vagia et al., 2016).

(1) *Human supervisory control of telerobots* that execute routine tasks, such as component manipulation on factory assembly lines. Operators send and update instructions to the system and oversee the telerobot as it performs a series of automated tasks in response to these commands. (2) *Remote control* of vehicles for non-routine tasks in hazardous or inaccessible environments. Operators can remotely control spatial, aerial, terrestrial, or underwater robots to perform several tasks, such as navigation or manipulation tasks in distant environments. (3) *Automated vehicles* transporting passengers such as cars, trains, or planes. (4) *Human–robot social interaction* involving social robots designed to entertain, teach, or assist individuals. In our research, we will focus on what Vagia et al. (2016) refer to as the remote control of vehicles for non-routine tasks, which we will term teleoperation. Let's now delve into the more specific definition of teleoperation.

1.2 | Teleoperation principles

The prefix *tele*, meaning *at a distance* or *far off* in Ancient Greek, adds a sense of distance to the associated element. Thus, teleoperation refers to an operation that can be carried out remotely. The operation involves controlling a robotic system capable of performing various manipulation or navigation tasks in an environment considered too hostile or inaccessible for direct human intervention. It is also employed when the operation is deemed too complex for a human, such as the precise manipulation of large, heavy, or, on the contrary, very small objects. Several definitions can be found in the literature, but if we consider the complete and simple definition provided by Sheridan et al. (1978) the remote robot can be described as *a vehicle having sensors and actuators for mobility and or manipulation controlled by a human operator, and thus enabling him to extend himself to physically remote or hazardous environment.* In telerobotics, although the terms are often subject to debate (Eglash, 2007), these systems are often described as master/slave systems. The remote robotic intervention system is referred to as the slave device and the control station as the master device.

The human operator's objective can vary from the direct control of the remote robotic agent to execute navigation or telemanipulation tasks, to its monitoring/supervision if it possesses a part of autonomy (Figure 1).

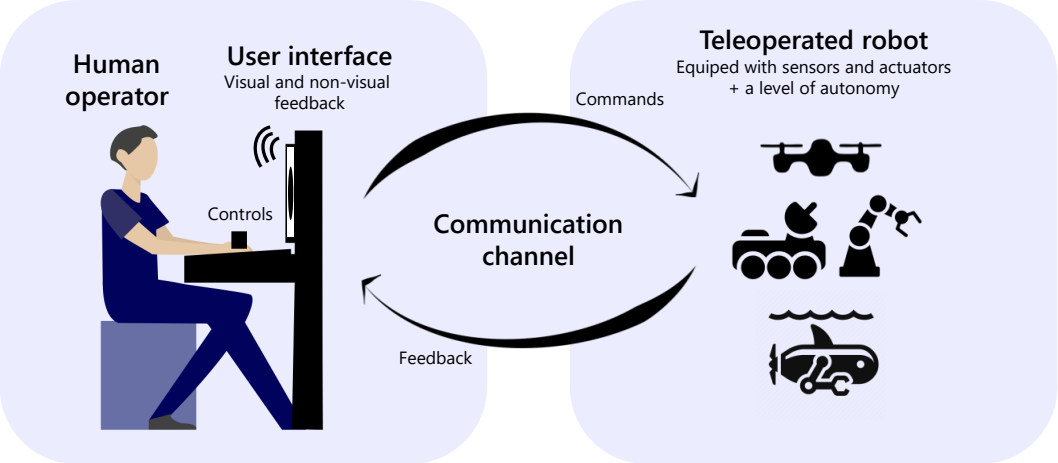

Figure 1: Schematic representation of the principle of robotic teleoperation. Information perception forms a bidirectional closed-loop process. A human operator controls or monitors the teleoperated robot via the user interface and controls. Commands can be transmitted through various communication channels such as radio, satellite, cellular networks, and wired or wireless internet connections. The robot executes the commands, and in return, the operator receives visual and non-visual feedback from the remote world and the robot's state. The teleoperated robots could be robotic arms or unmanned aerial, ground, or underwater vehicles.

Direct teleoperation

Direct teleoperation involves the immediate interaction between humans and robots. Standard unilateral teleoperation is characterized by an operator controlling the robot by transmitting commands through an interface. These commands can be transmitted through force applied to a controller, such as one or more joysticks, and/or by entering a new target state of the controlled system, such as its position or speed. The remote robot executes the commands, and in return, the operator receives detailed information about the robot's state and environment in real-time through visual and non-visual feedback. In the case of bilateral teleoperation, the robot includes force sensors and can reflect to the operator the reaction forces from the task being performed through haptic information. All this information can be presented on a visual display, such as a computer or tablet screen, and through controllers (Fong and Thorpe, 2001).

Supervisory teleoperation

Supervisory teleoperation is a form of remote control in which a robotic device with sensors, actuators, and a computer is capable of autonomous decision-making and control over a short period of time and in restricted conditions. The operator monitors the device from a distance and intermittently intervenes to directly control or reprogram it (Fong and

Thorpe, 2001). This can be achieved by giving the robot a certain level of local autonomy in obstacle detection and avoidance for navigation to a destination point for example. Supervisory teleoperation can also be combined with direct teleoperation to provide the operator with greater visibility of the remote environment. For instance, the supervision of a fully autonomous robot, such as an Unmanned Aerial Vehicle (UAV), combined with a directly controlled robot, such as an Unmanned Ground Vehicle (UGV), in multiple mobile robot systems is known as the leader-follower method. This can be implemented using a vision-based tracking technique, whereby the UAV can then provide the operator with another third-person perspective that could benefit from its situational awareness and teleoperation efficiency (Xiao et al., 2017).

Level of autonomy

Thanks to robotic technological progress, some functions and operations initially performed by humans were delegated to machines. The distribution of tasks and responsibilities between human agents and robots varies depending on the nature of the operation. In reality, there is no clear separation between direct teleoperation and the supervision of an autonomous robot. The different degrees of automation depend on the task at hand and can be characterized by a continuum of levels called Levels of Automation (LOA). Sheridan (Sheridan, 1992; Sheridan et al., 1978) was one of the first to identify these levels and proposes a classification into 10 LOA, ranging from fully manual control by the operator to fully autonomous control where the computer makes every decision and performs every action autonomously. More recently, Vagia et al. (2016) conducted a literature review on the existing taxonomies of automation levels, proposing a new classification of LOA by combining levels from different taxonomies developed in various domains (Figure 2).

Level of automy	Description	Description
Level 1	Manual control	Computer offers no assistance
Level 2	Decision proposal stage	The computer offers some decisions to the operator. The operator is responsible to decide and execute.
Level 3	Human decision select stage	The human selects one decision and the computer executes.
Level 4	Computer decision select stage	The computer selects one decision and executes with human approval
Level 5	Computer execution and human information stage	The computer executes the selected decision and informs the human
Level 6	Computer execution and on call human information stage	The computer executes the selected decision and informs the human only if asked
Level 7	Computer execution and voluntarily information stage	The computer executes the selected decision and informs the human only if it decides to
Level 8	Autonomous control stage	The computer does everything without human notification, except if an error that is not into the specifications arrives. In that case the computer needs to inform the operator.

Figure 2: Taxonomy of Levels of Automation of Robotics proposed by (Vagia et al., 2016)

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Vagia et al. (2016) discuss the nuanced interpretation of the terms *autonomy* and *automation*. They observe a lack of consistent usage of these terms in the literature and propose a definition based on the dictionary meaning of these words. An automation systems, as discussed earlier, *refers to a system that will do exactly what it is programmed by the programmer to do without having any choice or possibility to act in any different way dependent on the situation at hand. Its actions are predefined from the beginning, and it has no ability to change them in the*

future (Vagia et al., 2016). Whereas an autonomous system demands a higher level of computational sophistication as it was made to be able to *make a choice free from outside influence since they have some perceivable notion of "free will", (...) change its initially programmed way of action, to the degree that it has been decided a priori by the designer of the system* (Vagia et al., 2016).

1.3 | Brief description of teleoperation origins and evolution

Teleoperation systems have existed since the early 1900', but the first modern master-slave teleoperator was developed by Raymond C. Goertz and his team at the Argonne National Laboratory in the 1940s (Goertz, 1954; Hokayem and Spong, 2006) (Figure 3). This teleoperator was designed for the precise manipulation of radioactive materials while ensuring the safety of workers. The robotic arm was mechanically controlled, and the target was visualized through a protective window and/or a mirror.



Figure 3: Raymond C. Goertz using his teleoperator in the early 1950s for the manipulation of radioactive material, Courtesy Argonne National Labs, (Niemeyer et al., 2016)

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In the 1970s, the use of mobile teleoperation robots for military, space exploration, and industrial purposes significantly increased. Historical examples of teleoperation include the US Navy Cable Controlled Underwater Recovery Vehicle I, which was utilized in 1966 to retrieve an atomic bomb lost in the Mediterranean Sea at a depth of 2,900 feet, after a bomber collided with a tanker (Figure 4) or the Soviet Lunokhod rovers, used for moon exploration in the early 1970s (Figure 5).

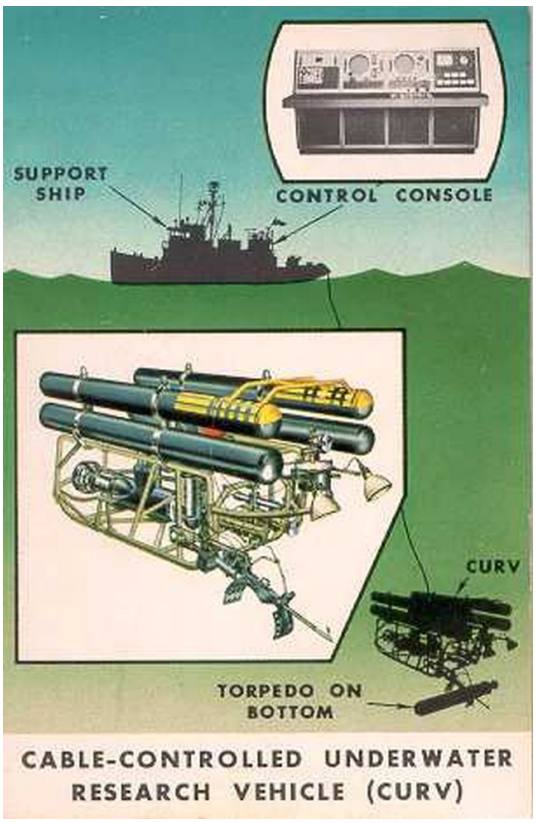

Figure 4: CURV, The Cable-controlled Underwater Research Vehicle robotic platform (Retrieved from https://cyberneticzoo.com).

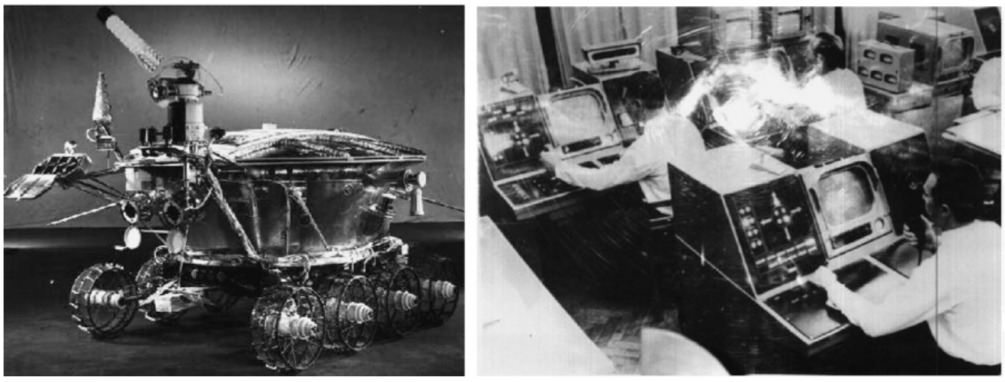

Figure 5: Lunokhod 1 and Lunokhod control station. The picture on the left shows Lunokhod 1, the first rover to be remotely operated from Earth, and the picture on the right shows the Lunokhod control station (NPO Lavochkina museum), as in (Fong et al., 2013).

Nowadays, the applications of teleoperation are continually expanding to meet the diverse needs of military, space, medical, and civilian sectors. The following section will provide an overview of the current and future uses of teleoperation technology.

2 | Teleoperation fields of application

Teleoperation has become increasingly relevant, leading to its widespread development and utilization across various domains. Technological advancements over the past eight decades, including the progress of devices, sensors, artificial intelligence, and efficient communication networks, have significantly improved the feasibility and effectiveness of teleoperation systems. This operational mode effectively meets the current specific needs of various fields, including civil, military, and industrial domains (see Lichiardopol (2007) for review).

2.1 | Medical applications

In the medical field, tele-surgery is used to perform highly intricate and complex procedures that would be challenging for surgeons to carry out manually. The extreme precision and high level of control allowed by robotic systems have motivated the development of telesurgery for a wide range of medical and surgical procedures (Avgousti et al., 2016). Some examples of robotic systems include the da Vinci System (Intuitive Surgical, Inc.), developed for minimally invasive laparoscopic surgery, and the DLR MiroSurge telesurgery system (Figure 6).



Figure 6: The DLR MiroSurge telesurgery system, DLR

Additionally, to address the limited availability of expert physicians and surgeons, long-distance telerobotic systems are used to perform procedures in remote and sometimes extreme environments. For instance, the MELODY robotic system (Adechotech, 2024) is a tele-echography system designed to compensate for the lack of ultrasound experts. The expert manipulates the ultrasound probe while the robot is maintained and positioned on the patient by a paramedic. A force sensor limits the pressure exerted by the robot on the

patient. The expert's interface includes a video-conferencing camera feed, allowing communication with the patient, as well as the ultrasound video feed. Another example is the RAVEN robotic systems (CITRIS and the Banatao Institute, 2024), which is a general-purpose telesurgery system tested by NASA in underwater conditions to evaluate its suitability for space (Avgousti et al., 2016). This system consists of two manual controllers (the PHANTOM Omni devices, SensAble Technologies, USA) and a foot-pedal controller. The visual interface includes a graphical user interface and a video feed from the operative site, see Figure 7.

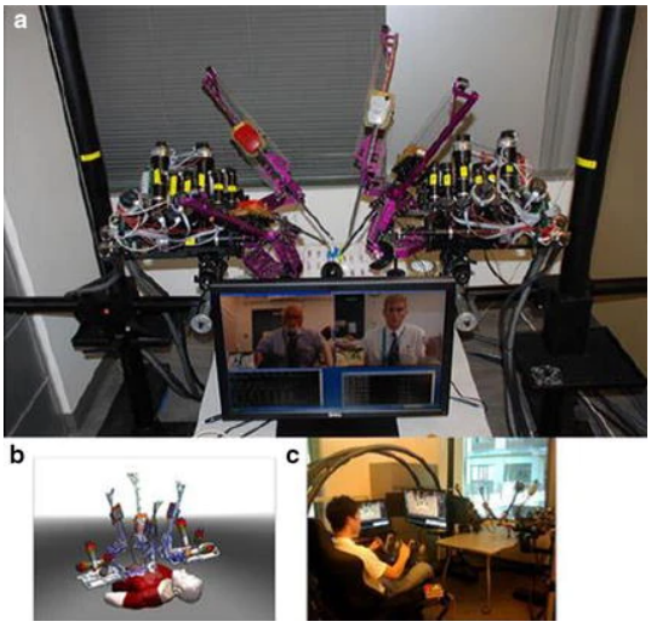

Figure 7: The RAVEN telesurgical system, retrieved from Avgousti et al. (2016)

2.2 | Military and security applications

In military operations, teleoperation is employed to enhance the safety of soldiers in war zones. Soldiers are trained to use and pilot drones for reconnaissance and surveillance missions, which are essential for gathering information about the enemy. Furthermore, recent military initiatives like FCAS (Future Combat Air System, Ministère des Armées (2024)) and MUM-T (Manned-Unmanned Teaming, Airbus (2024b)) aim to integrate manned and unmanned vehicles to execute specific missions (Figure 8, on the left). For instance, an UAV remotely operated from a helicopter or an aircraft could conduct reconnaissance missions to facilitate pre-emptive actions (Figure 8, on the right).

Likewise, in the security sector, teleoperation systems play a critical role. Given the increasing frequency of terrorist incidents, tele-robots are deployed to replace humans in



Figure 8: Future Combat Air System illustration, AIRBUS (left image). First LOI 5 demonstration for Airbus and Schiebel in 2018. A mission commander on the left controls a UAV using a computer screen placed in the aircraft cockpit (right image).

bomb disposal tasks (Figure 9). They can also assist law enforcement in surveillance, pursuit, and arrest missions, including deploying a gas cloud if needed (Lichiardopol, 2007).

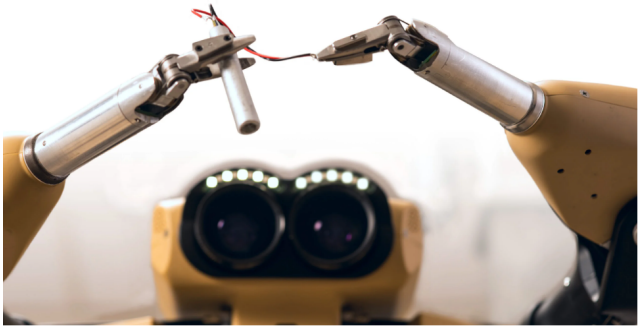

Figure 9: Taurus, a bomb disposal robot piloted with a virtual reality headset, SRI International

The International Disaster Database (2023) has documented a recent surge in natural disasters linked to weather and climate. In these disaster-prone environments, the use of remote-controlled systems to support search and rescue operations is crucial (Liu and Nejat, 2013). For instance, the European project SHERPA (Figure 10) is dedicated to the development of a mixed robotic platform, both terrestrial and aerial, designed to assist humans in rescue activities in alpine environments. The drones create 3D maps of the rescue area, while ground vehicles accompany the rescuer, serving as a transportation module for equipment and communication devices (Marconi et al., 2012).

2.3 | Industrial applications

In the industrial sector, various systems, such as underwater pipelines and nuclear facilities, require regular maintenance (Shukla and Karki, 2016). These systems are often sit-

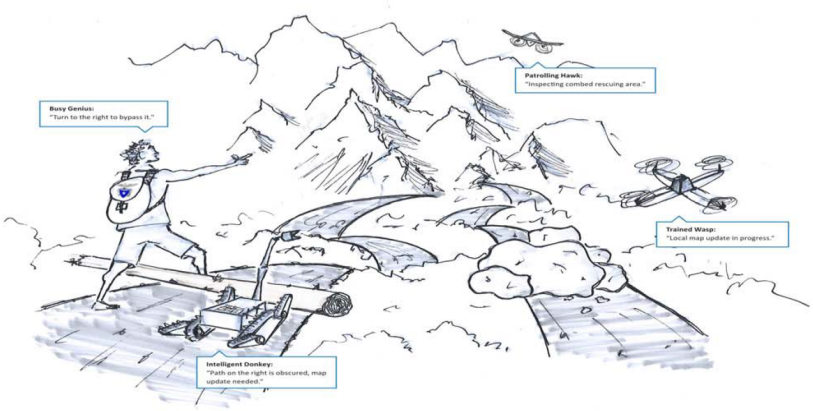

Figure 10: Representation of the SHERPA team (Marconi et al., 2012).

uated in hazardous or hard-to-reach locations, posing significant challenges for human workers attempting to access them. To enhance safety, robots can be deployed to perform essential emergency or routine inspections prior to human intervention. For example, Remote Operated Vehicles (ROVs) are highly maneuverable underwater machines commonly used for system inspection, manipulation, and oceanographic exploration (Lichiardopol, 2007; Shukla and Karki, 2016) (Figure 11). Telerobotics can also minimize human exposure during the manipulation of radioactive materials (Tokatli et al., 2021). Additionally, robotic teleoperation can be utilized in assembly lines across various sectors. For instance, teleoperated robots can perform surface treatments in the automotive sector González et al. (2021) or handle micrometer-sized objects in applications ranging from materials science to electronics (Bolopion and Régnier, 2013).

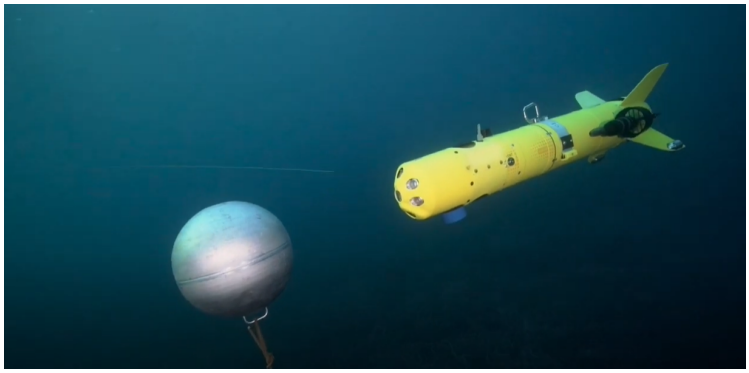

Figure 11: Screenshot from a YouTube video showcasing the SeaScan MK2, a remotely operated vehicle designed for underwater mine identification systems, demonstrating its capabilities in maritime operations, ECA Group (2024)

2.4 | Spatial exploration

Similar to oceanographic exploration, spatial exploration heavily relies on tele-robotics (Global Space Exploration Conference, 2024). We are witnessing the dawn of a new era in space exploration, as space agencies have taken up the challenge of developing the systems and capabilities necessary to explore beyond Earth's orbit. Through the ARTEMIS programs I, II, and III, aiming to land astronauts on the Moon by 2026, scientists will gain invaluable insights into establishing a new community on another cosmic shore; knowledge that could eventually guide the planning of manned space missions to Mars (NASA, 2019).

Astronauts have demonstrated their extensive capability to function and perform maintenance tasks during extravehicular activities. However, relying solely on astronauts for these operations within the scope of upcoming large-scale projects would be too costly and risky. Hence, the teleoperation of remote robots from control stations on Earth, aboard a space station in orbit, or in Lunar or Martian habitats presents a viable solution (Figure 12).

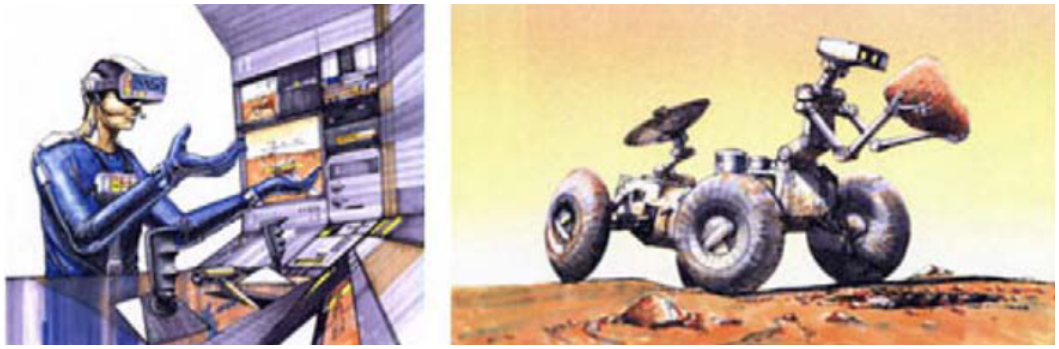

Figure 12: Teleoperation on Mars, painting by Carter Emmart, courtesy of NASA Ames Research Center, as in Landis (2004)

Space telerobots could then perform several exploration or maintenance operations for missions in orbit, deep space, or on surface environments (Fong et al., 2013). For instance, the teleoperation of the robotic arms Canadarm 1 and 2 over the years has enabled the deployment and retrieval of payloads, maneuvering to support astronauts during EVAs, satellite repairs, construction of the International Space Station (ISS), and facilitating inspections of shuttle components inaccessible to the crew (Figure 13).

In addition to being less costly and risky, employing space telerobotics offers a scientifically more robust alternative compared to on-site operations. Indeed, if robots are sent to explore the planet, there will be no need to implement human-rated *Mars landers* and *Mars ascent* vehicles. Consequently, the requirement for VTOL (Vertical Take-Off and Landing) spacecraft pilots will be reduced, allowing more space to be allocated for biologists and geologists. Additionally, biologically, this approach ensures the validity of sample non-contamination and preserves the Martian biota, while enabling a (remote) presence on a

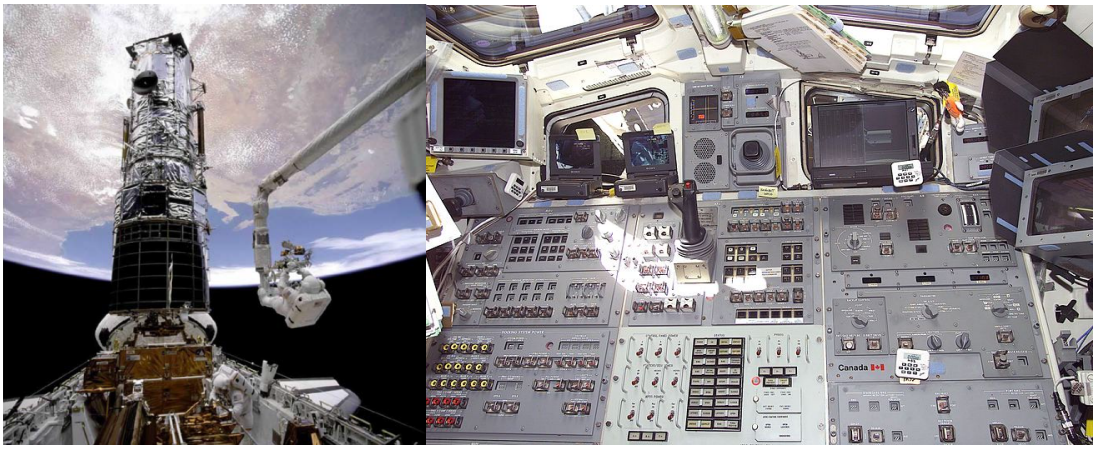

Figure 13: The Canadarm and its control station on the ISS. Story Musgrave being raised to the top of Hubble Space Telescope by the Canadarm (left image), STS-61 EVA Hubble Repair mission 1993 and the Canadarm control station on the ISS (right image), from (Jorgensen and Bains, 2011).

larger surface area (Landis, 2004).

While awaiting the establishment of lunar and Martian orbit stations, scientists have deployed multiple planetary rovers to explore space environments beyond human reach. As part of NASA's Mars Exploration Rover (MER) mission, the Spirit and Opportunity rovers were sent in 2004 to search for evidence of the past presence of liquid water on Mars. Due to the time delay, which can exceed 20 minutes, there was a need to implement a high level of automation in the rovers. However, once in orbit around the target planet, the time delay will be sufficiently short and negligible to enable real-time teleoperation, akin to that between the ISS and Earth. In this regard, as part of a Russo-German collaboration, the ROKVISS projects (RObotik-Komponenten-Verifikation auf der ISS, DLR, Oberpfaffenhofen) and their extensions KONTUR-1, -2, -3 (in collaboration with the RTC) aim to provide answers regarding real-time communication over the distance between the ISS and Earth. They also focus on designing a controller to mitigate the effects of time delays and loss of proprioception during teleoperation from space. In these projects, operators and astronauts were required to control the ROKVISS robot from Earth or the International Space Station using a force-feedback joystick (Riecke et al., 2016, 2020).

2.5 | Telepresence

Ultimately, teleoperation fulfills modern societal expectations by meeting our needs for remote presence. *"Telepresence is about the sense of being in another environment. In particular, robotic telepresence offers the means to connect to a remote location via traditional telepresence with the added value of moving and actuating in that location. A facet of robotic telepresence is social robotic telepresence where the primary aim of the system is to foster a social interaction*

between individuals" (Kristoffersson et al., 2013). Telepresence robots, for instance, enable remote assistance and intervention in conferences or meetings. The BEAM (2024) robot has been utilized by companies such as Google, L'Oréal, Cap Gemini, and the Miramont Family Medicine clinic Siwicki (2018), enabling doctors to consult with patients remotely. Telepresence robots also offer opportunities for children unable to physically attend school (hospitalized or facing chronic illness). These enable remote presence in the school environment, allowing participation in classes and even socializing during recess. In this context, the French Ministry of National Education and Youth initiated the TED-I project, providing these children with free access to a telepresence system (BEAM (2024), BUDDY (2023), and EDMO (2023)) operated remotely from the place of care or recovery. As of 2022, approximately 4,000 telepresence robots have been deployed across the French territory (TED-i, 2023) (Figure 14).



Figure 14: The Bubby Robot. Melvin attends his 3rd-grade class with the help of the robot Buddy at Paul Chevallier School in Rillieux-La-Pape, near Lyon, on March 3, 2023 (Olivier Chassignole, as in L'Express (2024))

3 | Assessing the effectiveness of teleoperation systems

The effectiveness of a teleoperation system depends on multiple factors, including the performance of the robot (such as sensor quality, transmission delay, and bandwidth), the expertise of the operator, and the overall collaboration between them (Steinfeld et al., 2006). Choosing the right metrics to evaluate these aspects accurately is essential for improving teleoperation systems and ensuring the success and safety of teleoperation missions.

An effective robotic system can be defined as one that enables an operator to achieve their mission objectives. However, the concepts of *effectivness* or *performance* alone do not account for the operator's experience and satisfaction while using the system. An ideal system must not only be high-performing but also pleasant and intuitive for the operator to use. In the research field of HRI, a concept that encompasses both performance and user experience is *usability*. Various definitions of usability can be found in the literature (Bevana et al., 1991). Brooke and collaborators propose defining usability as "*the effectiveness, efficiency, and satisfaction with which specified users can achieve specified goals in a particular environment*" (Brooke et al., 1990), as well as a simple 10-item scale, the System Usability Scale (SUS), that provides a global view of subjective assessments of usability. They define the effectiveness of the system as *the ability of users to complete tasks using the system, the quality of the output of those tasks*, its efficiency as *the level of resource consumed in performing tasks*, and user satisfaction as its *subjective reactions to using the system* (Brooke et al., 1996). The SUS scale offers a rapid assessment of usability, yet additional specific and interesting metrics can be gathered from the HRI literature. For instance, Steinfeld et al. (2006) and Murphy and Schreckenghost (2013) have compiled various measures to assess the usability of robotic systems in human-robot team tasks. Building upon Steinfeld, Murphy, and others' works comparing different teleoperation modes, we present in this chapter a list of measures for evaluating the usability of a teleoperation system, encompassing both performance and user experience. This list is not exhaustive but provides an overview of teleoperation task evaluation. We do not delve into metrics concerning the intrinsic performance of the robotic agent, as these relate more to robotics engineering rather than human factors.

3.1 | Teleoperation subtasks

Teleoperation missions can include various types of tasks. Drawing directly from the categories of HRI tasks proposed by Steinfeld et al. (2006), we identify different tasks that can be performed during a teleoperation mission. The first is *perception and understanding of the distant environment*, whether *(1) passive*, such as monitoring an autonomous robot, or (2) *active*, such as controlling a camera to view the environment or a part of the robot without direct interaction with the distant environment, for example, orienting a robot's solar panels. The second category includes (3) *navigation tasks*, which require the operator

to know where the robot is, where it needs to go, and how to get there. This necessitates both a global understanding of the robot's position (e.g., its localization on a map) and a local awareness of the characteristics of various obstacles or environmental hazards. Additionally, there are (3) *manipulation tasks*, involving the interaction of an actuator such as a robotic arm with elements in the distant environment. This requires a solid understanding of the characteristics of the manipulated items, such as their weight and texture, to ensure effective manipulation without damaging or dropping them. Moreover, in some cases, the use of teleoperation for telepresence allows the operator, via the robot, to interact with distant humans, which we refer to as (4) *social tasks*. Finally, (5) *management tasks* involve the coordination and management of different robots and operators involved in a mission.

To evaluate the usability of a teleoperation system during these tasks, various metrics can be collected. Within each type of task, we propose categorizing these metrics into subjective measures (based on individual perceptions) and the objective behavioral (based on operation) and physiological measures (collected from physiological responses that may reflect the operator's mental state). These metrics are summarized in Table 2.

3.2 | Common measures

Subjective measures

Throughout the literature, we often encounter specific subjective metrics used to evaluate or compare teleoperation systems from a human factors perspective. These include situational awareness, workload, and telepresence assessment, each addressing different but essential aspects of teleoperation systems.

Situational Awareness Situational awareness (SA), initially studied in aircraft piloting contexts, refers to knowing what's going on and can be defined more formally as *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"* (Endsley, 1988a). SA involves three levels: perception, comprehension, and projection of a situation, and can be broken down as shown in Figure 15. The quality of pilots' and operators' SA is highly interrelated and can be limited by individual factors such as skills, training, and experience. Additionally, Endsley's decision model (Fig. 15 ,Endsley (1988a)) indicates that task-related factors including the system used, its capabilities, interface ergonomics, and the stress and workload of the task also play crucial roles.

If we apply Endsley's explanation from this Figure 15 to teleoperation scenarios, we can explain these levels, such that firstly, the operator perceives the nearby (interface) and distant environments through their senses, primarily vision in our case, and touch if a haptic joystick is used (*Level 1. Perception*). Then, based on this knowledge, the operator forms a holistic picture of these environments, understanding the significance of objects

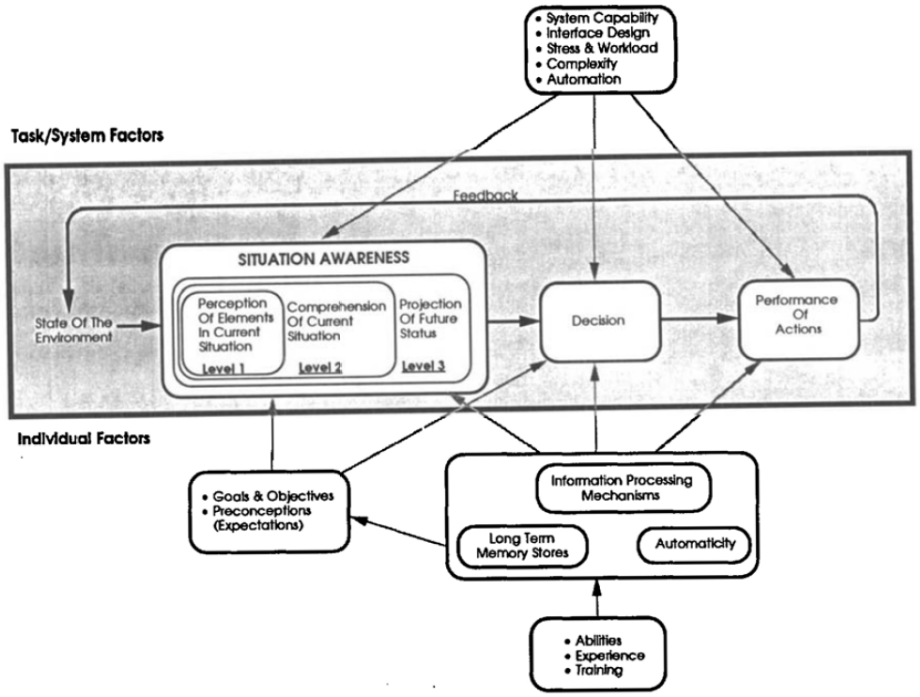

Figure 15: Model of situation awareness in dynamic decision making, from (Endsley, 1995).

and elements. For example, perceiving a flashing red light on the interface associated with signaling a critical error jeopardizing the mission (*Level 2. Comprehension*). Finally, based on what has been perceived and understood about the environments, the operator will project actions to take in line with their mission objectives (*Level 3. Projection*). For instance, seeing a large rock in front of the robot corresponds to an obstacle blocking the path, requiring future actions to navigate around it or remove it from the path.

One way to measure SA experimentally and mostly in laboratory settings is through the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1988b), which involves performing a task during which the subject must monitor various parameters. Periodically, the screen goes blank, and the subject is asked about the values of these parameters. However, it is important to note that this technique has its limitations, as the interruption of the task can significantly affect the participant's performance and does not accurately represent real-world scenarios where continuous monitoring is essential.

Workload Evaluating workload is commonly performed in ergonomics and human factors domains in human-robot interaction to assess the demands placed on an operator by a task. Over the last decades, research has focused mainly on evaluating *mental* workload in particular, which is not surprising given the increasing use of modern technologies, which place ever greater demands on cognitive skills (Young et al., 2015). There is no common

consensus on the definition of workload. One definition proposed by (Hart and Staveland, 1988a), authors of the NASA-TLX questionnaire widely used in ergonomics and HRI, states that workload is *"a hypothetical construct that represents the cost incurred by a human operator to achieve a particular level of performance"* (Hart and Staveland, 1988a). According to the authors, workload emerges from the interaction of numerous factors that subsequently influence operator performance. Figure 16 illustrates the various factors involved in operator workload and performance, showing that mental workload results from the interaction between task demands, the conditions under which the task is performed, and the operator's skills, behavior, and perception.

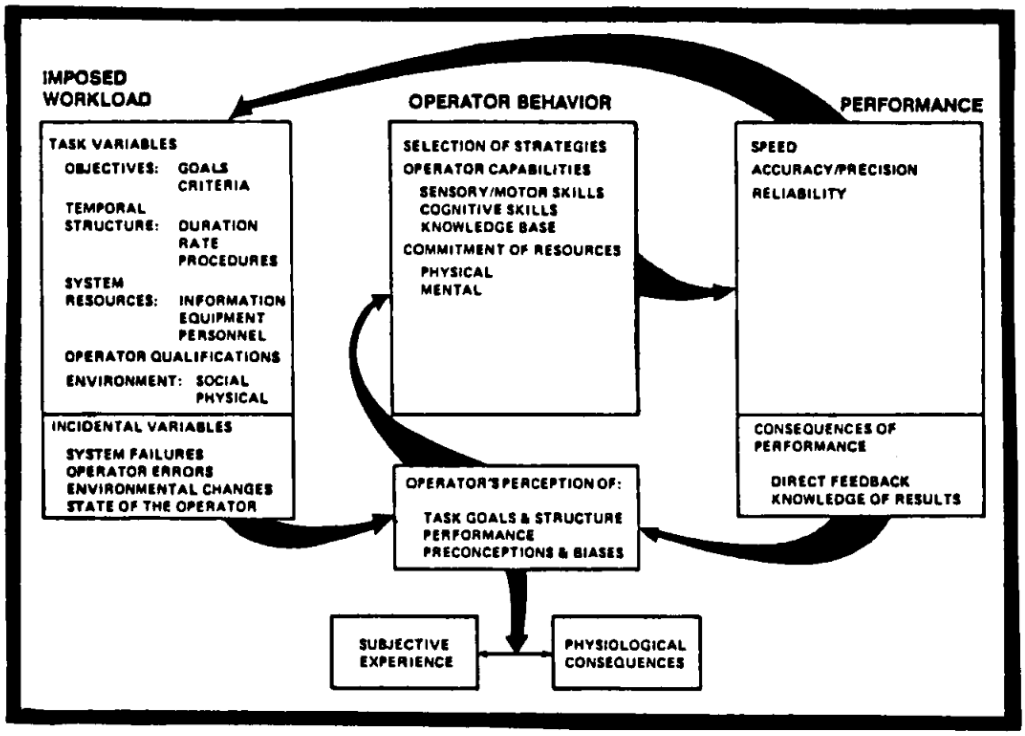

Figure 16: The conceptual framework for relating variables that influence human performance and workload from (Hart and Staveland, 1988a).

The authors then proposed to measure operators' subjective mental workload using a questionnaire. After completing the task under assessment, operators are asked to rate several items on a scale that represent various aspects of the workload: their perception of the mental, physical, and temporal demands of the task, their performance, the amount of effort required, and their level of frustration. The various elements are presented in detail in Table 1. Other measures of workload are presented in Young et al. (2015), such as the Subjective Workload Assessment Technique (SWAT) (Reid and Nygren, 1988) and the Rating Scale Mental Effort (RSME) (Zijlstra, 1995) questionnaires, as well as the performance

measurement on a secondary task (Wickens, 2002) and physiological measures (presented below, in the *Physiological measures* subsubsection).

Title	Endpoints	Descriptions
Mental Demand	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating. etc.)? Was the task easy or demanding? slow or brisk. slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Table 1: NASA-TLX Items. Description of workload measures from NASA-TLX (Hart and Staveland, 1988a).

Telepresence/tele-embodiment Telepresence and tele-embodiment have received significant interest in the literature on teleoperation and virtual reality (Sheridan, 1995; Sun et al., 2020). Telepresence in computer-mediated environments can be defined as *"a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience"* (International Society for Presence Research, 2024). In other words, telepresence signifies a sense of 'being there' in a virtual or remote environment. Embodiment corresponds to the sensation that our body is linked to our sense of self (Longo et al., 2008), therefore tele-embodiment refers to perceiving a remote-controlled object or avatar in the virtual world as one's own. An example of embodiment of an external object is the Rubber Hand Illusion (Botvinick and Cohen, 1998), where a visible rubber hand subjected to simultaneous tactile stimulation with the participant's hidden real hand is perceived as their own, a phenomenon also validated in virtual reality (Kocur et al., 2022). Numerous studies indicate that an increase in the sense of presence and embodiment could affect operational performance in virtual or remote environments. For instance, they could enhance performance in spatial cognition tasks (Maneuvrier et al., 2020), reduce workload (Ma and Kaber, 2006), improve situational awareness (Riley et al., 2004), and enhance dexterous performance in telerobotics (Toet

et al., 2020). Telepresence is a multidimensional concept that can be assessed in various ways, and several questionnaires are utilized in the literature. For further insights into the sense of presence in virtual reality and different methods of assessment, see Bouvier (2009) and Maneuvrier (2021).

Examples of other subjective measures Other measures of teleoperation system usability can be collected via user experience questionnaires. Questionnaires such as the UEQ (User Experience Questionnaire) allow users to express their feelings, impressions, and attitudes simply and immediately when experiencing the system studied (Laugwitz et al., 2008; Wojtusch et al., 2018). Other subjective experience questionnaires focus on aspects such as trust in the system (Rogers et al., 2017), especially when the robotic platform possesses autonomy (Endsley, 2017; Parasuraman and Riley, 1997), perceived performance, confidence and fatigue (Drascic and Grodski, 1993; Luck et al., 2006; Neumeier et al., 2019; Wang et al., 2004), quantitative and qualitative physical ergonomics assessment (posture comfort assessment) (Gholami et al., 2022), as well as observation notes regarding participant-expressed confusion and frustration (Drury et al., 2006).

Behavioral measures

Behavioral measures capture the operator's actions during a task, and their advantage lies in their objectivity, as they are directly observable during task execution. These measures can include performance metrics related to the task's objectives, as well as kinematic data on the operator's movements during interaction with the robotic interface. For instance, in Weber et al. (2016), the authors aimed to evaluate the effect of weightlessness on sensorimotor performance during a manual tracking task using a joystick (an application for space teleoperation). The participants' objective was to maintain a visual target, controlled by the joystick, along a predefined path. To assess performance, the researchers used metrics such as positional tracking error (or accuracy) and also analyzed the participants' kinematic movement profile by examining mean distance, speed, acceleration, standard deviation of speed and acceleration, as well as peak speed and acceleration. The results showed that, in their paradigm, "*in weightlessness, a higher average tracking error was documented, which had to be compensated with higher average speed to maintain the continuously moving target position.*"

Performance measures Performance measures commonly used in HRI that are applicable to teleoperation tasks include the percentage of the mission completed (effectiveness) and the time taken to complete the task or its components (efficiency) (Steinfeld et al., 2006). However, these measures are inherently tied to the objectives of the teleoperation missions, making them highly specific to the tasks being performed. Below, in section 3.3, we present examples of task-specific performance measures related to navigation, manipulation, passive and active perception, as well as social and management tasks.

Kinematic measures Kinematic measures refer to observable behavioral metrics during the movement of a teleoperator while interacting with the robotic interface. These measures relate to the position, speed, and acceleration of the movement, as well as their evolution over time during the teleoperation task. While these measures do not provide a direct assessment of performance, they often serve as valuable supports for interpreting and explaining the results. They can be collected by recording joystick positions (Weber et al., 2016), robot positions (Pfeiffer and Scaramuzza, 2021), or even manual movements (e.g., during reaching interactions with a touchscreen) using motion trackers, as demonstrated in Rider et al. (2003a).

Physiological measures

In addition to behavioral and subjective measures, physiological measures provide a deeper understanding of the operator's state. Mental states such as workload (Shaffer and Ginsberg, 2017; Tao et al., 2019) and mental fatigue (Ahn et al., 2016; Trejo et al., 2015) are often accompanied by physiological markers that can be objectively measured using specialized tools. These measurement tools generate signals, and from these signals, we can extract specific markers, also referred to as features. Commonly used measures include electroencephalography (EEG) and electrocardiography (ECG), which monitor brain and heart activities; oculometry, which tracks eye movement and pupil dilation; electrooculography (EOG), which focuses on characteristics of blinks and eye movement, and electrodermal activity (EDA), which records skin activity, including sweating. Interestingly, Meehan et al. (2002) successfully utilized the physiological reactions of VR users as a reliable, valid, sensitive, and objective measure of presence, employing EEG, ECG, and skin conductance.

3.3 | Task specific measures

Navigation Tasks

During a navigation task, subjective measures may include evaluating the operator's knowledge and awareness of the robot's both general and local location in the remote environment (Steinfeld et al., 2006). In addition, behavioral measures can encompass both driving and navigation errors. These can include the percentage of completed navigation tasks, area coverage, deviations from the planned route, instances of backing up or stopping when lost, successful avoidance of obstacles, collisions or failure to avoid obstacles, time taken to complete the task/subtasks, and over- or undershooting a turn (Steinfeld et al., 2006). Furthermore, we can add what Voshell et al. (2005) refer to as the fractal dimension of the trajectory; a measure used to describe the complexity of the path or shape traced by a remotely controlled robot from point A to point B in a complex environment. This method was previously employed to analyze the tortuosity of animal trails, where a higher fractal dimension D indicates a more complex and tortuous path (Dicke and Burrough, 1988).

Passive perception tasks

Passive perception tasks involve perceiving and understanding information transmitted through the teleoperation system interface, as in monitoring tasks. Measures may include information detection, such as reaction time or the number of detected target information. Measures of understanding may involve success in recognition or classification tasks, as well as the time required for identification. Additionally, measures may assess perception of extent such as accuracy and precision of judgments regarding sizes, depths, and distances. Perception measures may also encompass motion perception, whether of the teleoperated robot's motions (ego-motion) or of motions of elements in the remote environment. Measures related to the perception of the robot's attitude, orientation, and velocity can also be considered (Steinfeld et al., 2006).

Active perception tasks

Active perception involves a level of control over the robotic platform by the operator, whether solely controlling the camera while the robot moves autonomously or controlling the entire robot. In these tasks, evaluation measures for the teleoperation system similarly include errors and reaction times for perception and identification. Additional measures include assessing the effort required to detect and identify a target, where effort corresponds to the amount of camera or robot movements during the task (Steinfeld et al., 2006).

Manipulation tasks

For manipulation tasks, Steinfeld et al. (2006) suggest evaluating the number of contact errors or collisions between the manipulator and the environment, as well as assessing a teleoperation system by measuring the degree of mental computation required for task completion (see section *Degree of mental computation*). Another valuable measure would be robot maneuverability, which involves evaluating its position, velocity, and force regulation during the task as described by Sun et al. (2020).

Social tasks

The objective of an operator during social tasks is to see the remote environment and also to be seen to interact effectively with the humans present in that environment. Consequently, the measures should assess the quality of interactions with humans in the remote environment as well as the perception of the robot by the remote humans. They can include the assessment of the human's perception of the robot's compliance (social characteristics such as appearance and adherence to norms) and trust, observations of the type of social interaction the operator manages to have in the remote world, the assessment of the emotional state of the humans interacting with the robot, the time needed to capture the attention of humans as well as the duration of the interaction (Steinfeld et al., 2006).

Management tasks

Measures for management tasks can include the number of robots with similar capabilities a human can control (also called fan-out, (Olsen Jr and Wood, 2004)) or the number of humans required to control a robot, the time between the operator recognizing a problem and intervening, the time between the robot requesting help and the operator's intervention (Steinfeld et al., 2006), as well as the risk to humans in the remote environment (Murphy and Schreckenghost, 2013).

Tasks	Behavioral measures	Subjective measures	Physiological measures
Metrics common to all types of tasks	Percentage of the mission accomplished (effectiveness) Time required to complete the task or its components (efficiency) Percentage of assistance requests made by the robot Percentage of assistance requests made by the operator Number of operator interruptions considered non-critical Time in autonomous operation Time in direct control Time in unscheduled direct control Productive time vs. overhead time Kinematics Measures (speed, acceleration, jerk)	Situational Awareness Workload Telepresence and Tele-embodiment User experience questionnaires Perceived performance Confidence Fatigue Trust in the system Physical ergonomics assessment Confusion and frustration expressed by users Evaluation of the quality of the information received	EEG, fNIRS, ECG, Eye Tracking, EOG, EDA
Navigation	Percentage of navigation tasks successfully completed Coverage of area Number of deviations from the planned route/backing-up/stopping when lost Number of obstacles that were successfully avoided Number of obstacles that were not avoided /collisions Time to complete the task/subtasks Over- or undershooting a turn Fractal dimension of the trajectory (describes the complexity of a path or shape)	Knowledge of the general location of the robot in the remote environment Awareness of characteristics of nearby obstacles and hazards	
Passive perception	Detection of signals: Reaction Time to detect, % or number of detected targets Recognition and classification of elements, time to identify Accuracy and precision of judgment of sizes, depth, distances Judgment of egomovement and movement of objects in the environment Clear perception of the robot's attitude, orientation, and velocity		
Active perception	Time and effort (amount of camera and/or robot movement) to detect a target Time and effort spent identifying targets Identification errors: % or number of incorrect and missed targets, etc.		
Manipulation	Number of contact errors/collisions between the manipulator and the environment Maneuverability Dropping a transported item	Degree of mental computation	
Social	Type of interaction and social context Compliance (social characteristics such as appearance, adherence to norms, etc.) Time to capture the attention of humans in the remote environment Duration of the interaction	Assessment of the emotional state of the humans interacting with the robot Trust in the robot	
Management	Number of robots controlled by a human or number of humans needed to control a robot Time between the operator recognizing a problem and intervening Time between the robot requesting help and the operator intervening	Operator's ability to accurately and quickly identify the appropriate level of autonomy	

Table 2: Summary of examples of behavioral, subjective, and physiological metrics commonly used in the literature to evaluate teleoperation in HRI).

4 | Challenges and solutions

The rise of teleoperation systems is accompanied by a growth in research literature aimed at understanding and addressing certain challenges operators face. In this regard, several reviews or meta-analyses propose lists of various human-related factors influencing performance during a remote control task such as Arrabito et al. (2010); Chen and Barnes (2014); Chen et al. (2007); Oncu and Yildiz (2014); Woods et al. (2004), and Kari and Steinert (2021).

In this section, we propose a classification of the main challenges and proposed solutions associated with teleoperation as documented in the existing literature. Our proposed classification categorizes these challenges based on five dimensions: the individual characteristics of the operator (*who*), the nature of the task to be performed (*what*), the robotic system used (control interface and the robot) (*how*), the remote robot's environment (*where*) and operators environment (*wherefrom*).

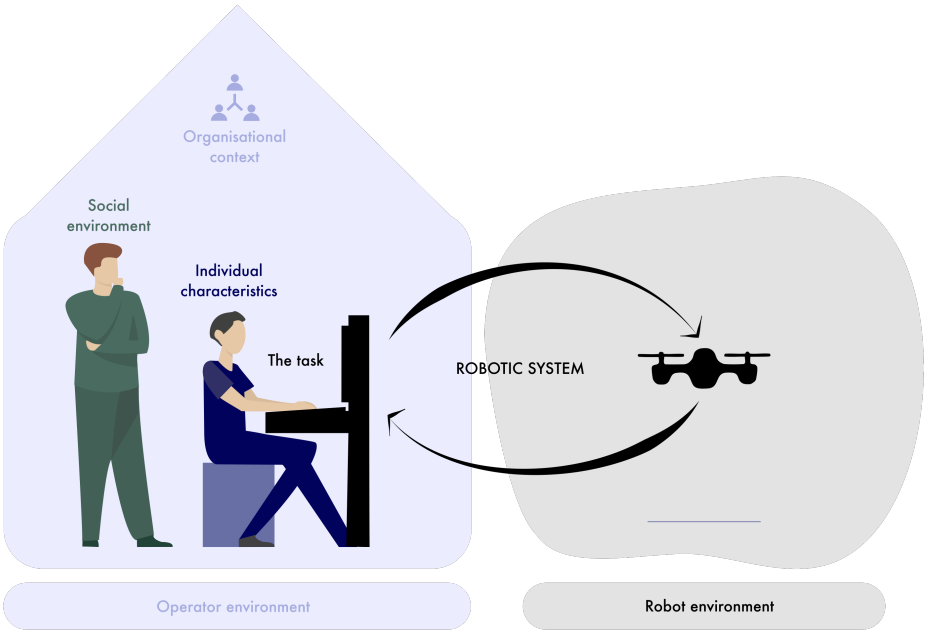

Figure 17: Representation of the key dimensions influencing teleoperation.

4.1 | Challenges related to individual characteristics (*Who*)

The success of a teleoperation mission, like any mission involving human beings, depends on factors related to the individuals chosen to carry out the mission. Drawing from knowledge reported in the literature, we have identified five distinct aspects associated with the individual characteristics of the operator.

Trust

The first of these characteristics concerns the degree of trust the operator places in the robotic agent. This trust depends on technical choices made during the design of the system and the mission, such as its level of autonomy and transparency in automation, its performance, and the overall workload of the operator. However, individual cognitive and psychological factors of the operator can also contribute. This includes factors such as age, personality (e.g., introversion versus extroversion), self-confidence, perception of automated systems, the operator's affective states, their level of stress, and fatigue (section 4.3) (Arrabito et al., 2010; Chen and Barnes, 2014; Kari and Steinert, 2021).

Social skills

An operator's social skills can influence teleoperation (Arrabito et al., 2010; Oncu and Yildiz, 2014). Effective collaboration within the team or with external agents is often required during these missions, necessitating clear and respectful exchange of information, even in high-pressure situations. For instance, when a remotely operated vessel must identify itself to other vessels through radio, clear communication in the appropriate language is essential (Kari and Steinert, 2021).

Operator's knowledge and technical skills

A crucial element for a mission's success concerns the operator's knowledge and experience in executing the task. This includes the quality of training, the operator's readiness for the mission, and their prior experience (Arrabito et al., 2010; Oncu and Yildiz, 2014). In other words, does the operator possess all the required knowledge and skills to accomplish the task effectively?

Adverse physiological states

This category includes all medical and physiological abnormalities, whether induced by medication, illness, exposure to toxic environments, or other factors (Arrabito et al., 2010; Oncu and Yildiz, 2014).

Poor cognitive and psychological states

The final component we propose includes factors related to the operator's cognitive and psychological states before and during the operation (Arrabito et al., 2010; Kari and Steinert, 2021; Oncu and Yildiz, 2014). This involves their levels of vigilance, fatigue, stress, anxiety, emotional and motivational states, and the presence of certain syndromes or psychological and psychiatric conditions (such as depression or burnout).

4.2 | Challenges associated with the teleoperation task (*What*)

Challenges associated with the nature of the task

As presented in section 2, teleoperation applications are diverse, and teleoperation tasks can vary greatly. These tasks can range from monitoring to robot control, involving manipulation or navigation. Therefore, for various reasons, some are inherently more complex to perform than others. For instance, they may differ in duration, required skills (manual precision, spatial mental rotation, amount of information to process), or level of stakes involved (property damage, life and safety of oneself or others). However, despite the wide variety of teleoperation tasks, a common characteristic among them is the need for remote perception of the robot and/or the distant environment, which presents its own challenges.

Challenges associated with remote perception

Humans, along with most organisms, perceive their environment through various sensory channels, a process referred to as multisensory integration. All visual, auditory, somatosensory, vestibular, gustatory, and olfactory sensory systems gather various information from the environment and subject states. These sensory inputs are combined and complement each other. The redundancy of information from different sensory channels, all reporting about the same event, validates that event's occurrence. For instance, in a noisy environment, observing the movement of someone's lips during a conversation can help to understand them better (Schwartz et al., 2004). In some situations, if visual localization (estimating the origin of sound via vision) is not clear or reliable, this bimodal integration can also trick us. This occurs when ventriloquism creates the illusion of a talking puppet. This phenomenon also holds in the reverse sense; if auditory localization is poor, visual localization will dominate. However, in most cases, the precision of bimodal perception is usually better than when the presentation is unimodal (Alais and Burr, 2004). Therefore, multisensory integration and interaction is essential for an accurate understanding of our environment.

When teleoperating, operators must perceive, understand, and sometimes interact with the remote environment through the eyes and other sensors of the robotic platform. However, seeing through a remote camera does not offer the same level of performance as having a human observer on-site. Perception is an active process that involves the interaction of multiple sensory systems. In remote perception, stimuli are impoverished, perception could then be distorted and lead to perceptual ambiguities. In this regard, the review Woods et al. (2004) highlighted the main perceptual ambiguities arising from the disconnection between the robot and operator environments, as summarized below.

Scale ambiguity Coupling visuo-vestibular cues allows us to simultaneously obtain information about head's acceleration and position (vestibular cues) and head speed through

optical flow (visual cues). This process aids in accurately estimating our body's position and movements in space, aiding in natural scaling. However, In remote perception, this vestibular cue is lost. Woods et al. (2004) further suggests that it's not only the absence of vestibular information, but rather the conflict between vestibular and visual cues that impacts scale perception.

Poor perception of depth and relief Every being endowed with binocular vision relies on binocular disparities, meaning the differences in positions between the images projected onto the right and left eyes, to assess distances and thus estimate the concept of depth. This visual process, known as binocular stereopsis, allows us to perceive the three-dimensional aspects of our surroundings. However, when observers view a scene in two dimensions, such as on a screen, this perception leads them to believe that everything presented is on the same flat plane. Although other cues may be present in the visual scene to aid in the perception of depth and relief, they are significantly reduced in remote perception (Woods et al., 2004).

Perception of speed To perceive self-motion speed, we rely on optical flow visually perceived as well as prior knowledge and affordances about the height of our eyes. Usually, an operator has no sensory cues indicating the camera height in the remote environment, which can lead to misinterpretation of the robot's speed. As the author points out, "*an intermediate optical flow in the image could result from a small robot moving slowly or a larger robot moving relatively quickly*" (Woods et al., 2004).

Visuomotor coordination When a human being moves in a changing environment, the control of their gaze is adjusted to anticipate future movements and orient themselves towards areas of interest. If we need to run to catch a bus, we will look towards the bus, then towards our feet as we jump over a curb or other obstacles to avoid tripping, and then redirect our gaze towards the bus. The orientation of a robot's camera is not as fluid. Orientation changes are either done step by step, or the camera remains fixed on the area of interest (Woods et al., 2004)

FOV restricted Unlike natural vision, in remote perception, the angular or Field of View (FOV) is more restricted, limiting the observable portion of space from a specific point (Arrabito et al., 2010; Chen and Barnes, 2014; Woods et al., 2004). This phenomenon is commonly called the "soda straw" by operators. This constrained vision significantly impacts the perception of new events, alters navigation skills in new environments, and leads to the construction of incoherent spatial models. This arises from the restricted vision cutting off the extrafoveal field of view. As a result, attention can no longer be directed towards extrafoveal zones, crucial for determining where to look next. This limitation could diminish the ability to anticipate potential interferences with ongoing missions.

4.3 | Challenges associated with the robotic system (*How*)

Performance depends closely on the robotic system used to execute the mission. The workstation, interface, and remote robotic agent play key roles in how the operator interacts with the robot, which can potentially affect their performance.

Ergonomics of the workstation and teleoperation interface

As mentioned by Oncu and Yildiz (2014), the technological environment, including the ergonomics of the workstation and the interfaces through which the remote robot is controlled, can have a significant impact. For example, the desk or chair's design, the screens' position, or inadequate controllers can put the operator in poor conditions to effectively control the robot remotely. For instance, an alarm that does not account for the pilot's attentional deafness processes could go unnoticed and lead to incidents or accidents (Dehais et al., 2014).

Moreover, in their reviews, Steinfeld et al. (2006) and Murphy and Schreckenghost (2013) discuss certain characteristics of teleoperation interfaces, such as the incompatibilities between the stimulus and the response required from the operator, as well as the level of mental processing required by the teleoperator during interaction with the interface, which can affect performance.

Stimulus-Response compatibility Teleoperation involves a complex interaction between the operator and the machine, during which the operator processes information provided by the interface before executing an action related to their objectives. The compatibility between the provided information (stimuli) and the response executed by the operator, which Fitts and Seeger (1953) refer to as SR Compatibility, can impact operator performance (Murphy and Schreckenghost, 2013; Steinfeld et al., 2006).

The compatibility of S-R relations means that the combination of stimuli and responses allows for efficient information transfer. Fitts stated that *"human performance in perceptual-motor tasks is most effective when minimal information transformation (encoding and/or decoding) is required. This means that the information generated by successive stimuli should be well-suited to the set of responses demanded by the task, or conversely, that the set of responses should be appropriately matched to the characteristics of the stimulus source"* (Fitts and Seeger, 1953). For instance, Fitts found that combinations of stimuli and responses with similar and congruent spatial characteristics tended to increase SR compatibility observable in terms of accuracy, reaction time, and information loss per stimulus (Fitts and Deininger, 1954; Fitts and Seeger, 1953). He explained these phenomena as *"the response that an individual produces in response to a specific stimulus event can be viewed as influenced by two sets of probabilities: (a) the probabilities (or uncertainties) determined by the situational constraints defined by the experimenter's instructions, the reinforcements encountered during the experimental setup, and other aspects of the immediate context; and (b) the broader and more enduring expectancies or habitual responses*

shaped by the individual's experiences across various situations". This means that besides the expectations induced by the task at hand, other expectations govern participants' behaviors and choices that are linked to population stereotypes (Fitts and Deininger, 1954; Fitts and Seeger, 1953). While most of the stereotypes mentioned by Fitts are generally universal, it's important to note that some may be cultural. For instance, in some countries such as the United States, Canada, European countries, or Russia, the "on" position of a toggle light switch is "up", whereas in other countries like the United Kingdom, India, Australia, or China, it is "down". Consequently, certain combinations of stimuli may be perceived differently based on specific cultural stereotypes, potentially influencing performance in perceptual-motor tasks.

In addition, the results of Wallace (1971) show, that S-R compatibility tends to be maximized when the S-R pairings follow the same laterality in the environment. For instance, responding with the right hand to a red light on the left side of a panel affected response time compared to when the red light was presented on the same side as the hand used for response (even when arms were crossed). Such effects can also occur when the positions of responding limbs are specified solely by kinesthetic signals (tasks where subjects could not see the position of their upper limbs) (Wallace, 1972). Interestingly, this spatial compatibility can pose challenges not only between the stimulus (S) and the response (R) but also between the stimulus and an irrelevant distractor for task completion. Simon's paradigms have shown that people react faster and more accurately when the stimulus and a distractor (featuring directional cues) are presented in the same location as the response. This holds true even when the distractor is irrelevant to the task and presented in a different sensory modality (e.g., an auditory distractor in a visuomotor task). For instance, participants react more quickly to a light presented on the right side of a screen when accompanied by a tone in the right ear compared to a tone in the left ear (Simon and Rudell, 1967).

Furthermore, according to Wickens et al. (1984), when interacting with complex systems, operators must not simply respond to stimuli but integrate the signal into their mental representation of the system. He thus examined the compatibility between the stimulus, central processing information, and the response. Wickens supports the theory that information is processed and encoded in working memory either spatially or verbally, showing that tasks involving navigation and spatial localization were better achieved when the input was visual and the output manual, whereas tasks involving the retention of verbal information were better performed when the input was auditory and the output speech.

Degree of mental computation The complexity of some teleoperation tasks can be estimated based on the degree of mental computation performed by the operator. Examples proposed by Steinfeld et al. (2006) are mental rotation, rate tracking, and object-referent association in working memory. In this respect, Wickens et al. (2005) discuss the importance of reference frames used for visuospatial tasks, which are central to teleoperation missions, whether for navigation or manipulation tasks. Movements performed during a visuospa-

tial task can be defined in terms of spatial coordinates. This means that each movement can be located and oriented in a three-dimensional space using a system of Euclidean coordinates, including an origin (a reference point from which coordinates are measured) and three axes (x, y, z). A reference frame corresponds to a system whose coordinates share the same directional axes (x, y, z), but whose origin may vary. A scene can then be analyzed according to several reference frames, each with a different origin. Wickens explains that a teleoperation task inherently requires a combination of reference frames. These include the earth frame, the operator's egocentric frame, the joystick control frame, the visual display frame, and the robot frame. This combination of reference frames requires operators to perform coordinate transformations from one frame to another. An example could be performing a movement in the horizontal plane and perceiving the result on a vertical plane, akin to moving a mouse on a desk (horizontal plane) and observing the consequence on a computer screen (vertically oriented). Aligning or comparing these reference frames is cognitively demanding, and some transformations are more demanding than others. These demands can negatively impact operators' performance in terms of time, errors, and mental workload (Wickens et al., 2005).

Challenges related to the communication link

As mentioned earlier, the operator's perception is already limited by the lack of sensory redundancy or impoverished stimuli in their perception of the remote environment. They can only rely on the video feedback presented by the interface. Therefore, if this feedback is not accurate in timing (time delay) or provides a distorted representation of space (reduced bandwidth), the operator's perception and, thus, performance can be greatly impacted. For example, reduced bandwidth, below a threshold of approximately 15 Hz, has been reported to impact psychomotor and perceptual tasks. Below this threshold, studies report alterations in the estimation of positions, camera speed and motions, participants' spatial orientation ability, as well as their duration to complete a navigation task in a remote environment. Additionally, they may encounter difficulties in identifying objects and performing teleoperation tasks requiring manual tracing, tracking, and placement tasks ("peg-in-hole tasks") (Chen and Barnes, 2014; Moniruzzaman et al., 2022).

Time delay, latency, or lag is one of teleoperation literature's most frequently discussed issues. It corresponds to the time delay between sending the input command and the visible response on the teleoperation interface. Depending on the context, the time delay can range from milliseconds to several seconds. In general, latency has been shown to impact several aspects of teleoperation, with variable latencies being the more problematic. Some reported consequences include a shift in teleoperation strategy from continuous control to 'move and wait', and increased movement and completion time. Tasks such as navigation, manual tracking, pursuit, grasp, placement, and simulated driving, can undergo alterations. In addition, latency has been linked to degraded telepresence and increased motion

sickness due to signal disparities (Chen and Barnes, 2014; Kim et al., 2021; Moniruzzaman et al., 2022; Sheridan et al., 1978).

Autonomy and Automation of Robotic Agents

During their missions, operators may control and/or supervise more or less autonomous remote robotic agents. Despite autonomous telerobots' many advantages, their operational efficiency has some intrinsic limits. In 1997, in a review, Parasuraman and Riley (1997) explored how humans interact with automation, introducing their use, misuse, disuse, and abuse of automation. They identified that the way an operator chooses to use an autonomous agent depends on factors such as their mental workload, confidence in automation, and the risk associated with the decision to use automation.

Parasuraman and Riley (1997) also emphasize the complexity of generalizing these results to all operators, as these factors vary between individuals. For instance, the degree of trust placed in automation depends not only on the robot's performance but also on human factors such as personality, self-confidence, emotions, age, and perception of the automated system (Chen and Barnes, 2014). It has also been observed that in some situations, operators may either rely too much on automation (*misuse*) or, conversely, under-utilize it (*disuse*). Over-reliance on automation can lead to failure warning signs of malfunction are ignored. Over-reliance is influenced by workload, automation reliability, and consistency, as well as the salience of the automation status indicator. On the other hand, automation underutilization often occurs when too many false alarms are generated, undermining the credibility and reliability of the robotic platform and disengaging humans from its use. In the title *Humans and Automation*, Parasuraman extends the term *Human* to encompass not only operators but also automation designers and their implementation by managers. Thus, he addresses the *abuse* of automation, which refers to poor design and implementation of automation in the field that may not sufficiently consider the human aspect. These gaps could further contribute to inappropriate uses of automation by operators.

Endsley (2017) introduces the big challenge of automation: the Out-of-the-loop Loss of Situation Awareness. She states that *the more automation is added to a system, and the more reliable and robust that automation is, the less likely that human operators overseeing the automation will be aware of critical information and able to take over manual control when needed.* The lack of transparency in the operations of automatic systems, coupled with over-reliance on the system and the inherent passivity in supervisory tasks, leads to a misunderstanding of the system's actions, a decrease in attention allocated to the supervisory task, and an overall reduction in situational awareness affecting the operation. According to Ensley, giving the operator a more significant and active role would mitigate these effects.

There is abundant literature on the study of Human-Automation Interaction and Teaming. However, with the proliferation of increasingly autonomous or even intelligent robots, researchers in the field of HRI now distinguish between automation and autonomy to more

precisely analyze the various limitations that may arise from interacting with a particular autonomous robotic agent. O'Neill et al. (2022) conducted a literature review on human autonomy teaming to identify independent variables related to Human-autonomy-teaming compared to automation-teaming. Their findings generally indicated that studies comparing human-human teams and human-autonomous system teams revealed that teams composed solely of humans had better information communication and higher performance. A high level of autonomy in an agent, as well as the interdependence between both human and autonomous agents, resulted in better outcomes. The authors added that it is important to remember that these results may also be due to poor automation design that does not adequately consider human needs to perform appropriate functions. Therefore, further research in this area is needed.

Other consequences can result from the use of automation and autonomous robots. Monitoring an autonomous robotic agent requires the operator to continuously oversee a large amount of information simultaneously, which could lead to increased mental workload and the possibility of missing important information. Another concerning limitation is the degradation of operators' skills. Using autonomous systems for an extended period can habituate the operator to rely on the system to perform certain tasks; due to lack of practice, they may be less proficient if they unexpectedly need to regain control of the robot (Arrabito et al., 2010).

Robustness of the Robotic Agent

Finally, in this category, we can also include the reliability and robustness of the robot, as technical limits and failures could compromise the mission (Oncu and Yildiz, 2014; Woods et al., 2004).

4.4 | Challenges associated with the robot's environment (*Where*)

Factors influencing camera feedback

Firstly, the robot's environment or operational environment can affect the operator's perception of the distant world. In this category, we consider all characteristics of the remote environment that can restrict the operator's vision, such as inclement weather, insufficient or excessive brightness, and vibrations from the onboard camera (Oncu and Yildiz, 2014). These factors can degrade the visual feedback quality and, consequently, affect the operator's perception of the remote world. Moreover, the farther the remote environment is, the more likely the video feedback will be affected by poor bandwidth and significant latency (Chen et al., 2007). Both can strongly impact the operator, as mentioned in section 4.2 dealing with issues related to poor perception.

Likelihood of dangerous or unexpected events

Additionally, we could add the likelihood of a dangerous or unexpected event as an important factor to consider during teleoperation, especially in changing or hazardous environments. These environments increase the likelihood of an incident occurring, along with the operator's stress, requiring increased adaptability on their part. For instance, the results of (Chae et al., 2024) showed that a challenging work environment (characterized by sloping terrain and multiple obstacles) impaired teleoperation performance and mental workload (as measured by NASA-TLX).

4.5 | Challenges associated with the operator's environment (*Wherefrom*)

In addition to the technical environment, an operator's organizational, social, and physical environments can also influence their performance.

Organizational framework

The organizational framework of an operator refers to the set of conditions, procedures, and practices implemented by an organization to structure and organize its missions. For example, the way an organization trains its agents, organizes teamwork, drafts procedures, and plans missions will significantly impact mission effectiveness (Arrabito et al., 2010). Furthermore, higher organizational levels have also been linked to pilot error in aviation (Li and Harris, 2006).

Social environment

Peer and supervisor pressure, surrounding noise, and insufficient or ineffective communication from the team are also factors related to the work environment that can affect the operator's effectiveness (Arrabito et al., 2010; Kari and Steinert, 2021; Oncu and Yildiz, 2014).

Physical environment

Given that the robot's and operator's physical environments are dissociated, we also include the operator's physical environment in this section. This category encompasses all the physical characteristics of the operator's environment that could present challenges, such as noise caused by surrounding engines NASA (2010), altered gravity levels (teleoperation from the ISS, Riecke et al. (2020)), vibration (Conway et al., 2007; Grether, 1971; Nakashima, 2005), and motion (Chen et al., 2007).

While other characteristics of an operator's environment tend to be regularly cited, during our literature review only Chen et al. (2007) mentioned a challenge regarding the effect of motion. It discusses a series of studies conducted by the U.S. Army Research Laboratory

on the effect of Army's command and control vehicle (C2V), and a demonstration by the Lead System Integrator of the FCS for the Concept and Technology Development phase, during which the operator teleoperated robotic vehicles from a moving command vehicle (McDowell et al., 2007). The results of these studies highlight the challenges that vehicle movement can pose to the cognitive performance of operators. These studies will be presented in more detail in the following chapter.

4.6 | Proposed solutions

The literature seeks to propose improvements to teleoperation systems to address various identified issues and ensure good operational performance. Various approaches have been attempted to enhance teleoperation. These improvements can occur at different levels, including hardware enhancement (physical and electronic components of the robot), software enhancement (control architecture and algorithms), as well as user interface ergonomics, encompassing visual displays and controllers. We will mainly focus here on improving user interfaces. The choice of the proper interface depends significantly on the task at hand. While some improvements target common issues across all teleoperation tasks, such as reducing delays or improving visual interfaces for better situational awareness, interfaces suited for navigation may not work well for tasks involving robotic arm manipulation. Here are some examples of proposed user interface enhancements that are applicable across various teleoperation tasks and tailored to specific task requirements.

Viewing mode and display type

Most teleoperated systems are unidirectional and use a monocular camera setup, displaying video streams captured from the robot's attached camera. Research dedicated to ergonomics in video games, piloting, and teleoperation indicates that different visualization displays and viewing modes could significantly enhance users' situational awareness and performance.

Stereoscopic 3D vision In teleoperation, monocular camera setups are traditionally used due to their low cost and minimal bandwidth usage, helping to limit time delay. Most of the time, monocular depth cues are sufficient to obtain an accurate representation of the remote environment. However, if these monocular cues are missing or ambiguous, the depth perception may be altered (Woods et al., 2004). Providing the operator with a stereoscopic vision would provide binocular cues in addition to the monocular ones and then help obtain more information for a three-dimensional perception of the distant environment. In the fields of human factors and human-computer interaction, as well as in medical research, these systems prove to be beneficial for tasks involving the manipulation of objects, whether real or virtual, close to the user. They are particularly useful in contexts where tasks are complex, difficult, or unusual for operators. For example, novices seem to

perform better in 3D compared to non-stereoscopic (2D) visualization (See McIntire et al. (2014) for a review).

A way of re-creating stereoscopic vision in teleoperation is to use binocular cameras. They will provide two images of the remote environment, providing stereoscopic information and helping with distance and depth perception. For instance, Luo et al. (2021) conducted a study aiming to compare monoscopic and stereoscopic views and display types (immersive and non-immersive VR) for UGV teleoperation in real-time navigation tasks that require avoiding moving and static obstacles. They found that the use of a stereoscopic view in an immersive display enhances user performance.

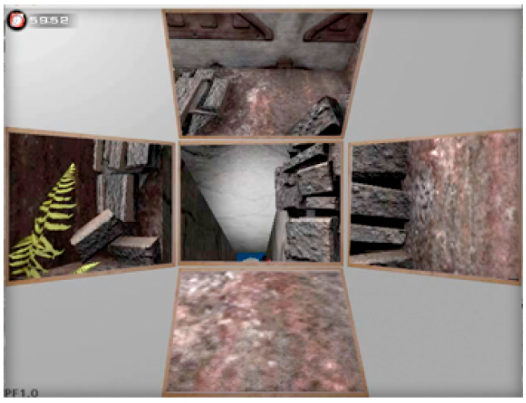

Figure 18: A proposition of teleoperation visual displays called Perspective Folding. This interface allows to *re-embed the observer in the scene and re-introduce peripheral optic flow cues that signal movement relative to the environment* (Voshell et al., 2005).

Camera FOV and viewpoint Expanding the field of view provided by the remote camera, and consequently, the amount of visual information accessible on the display is a way to increase the sense of immersion in virtual reality, navigation performance, spatial representation (Lee Pazuchanics, 2006), and the control of lateral position in negotiating sharp curves (Van Erp and Padmos, 2003). This can be achieved by increasing the number of cameras present in the remote environment and/or by using wide-angle cameras. For example, Voshell et al. (2005) proposed a visual display that interfaces with an array of five cameras (oriented at different angles) to provide a "wrap-around" effect, thus integrating multiple views into a global reference frame (Figure 18). Another way to increase the amount of visually accessible information for the operator, or to ensure that the information necessary for the successful completion of the task is included in the video feed, is to automate the viewpoint adjustment. In this way, the camera's viewpoint shifts from a fixed point relative to the robot to a flexible point, which will be automatically directed to the anticipated spatial location and adjusted based on the characteristics of the environment and the task, as seen in Rahnamaei and Sirouspour (2014).

Perspective In the literature, various terms are employed to describe the different perspectives of visualization. In this manuscript, we will adopt the following terms and definitions (Figure 19): When the video feed comes from a camera mounted on the robot, it's referred to as a first-person perspective (1PP). If this camera is placed further away from the robot, generally offering a wider field of view, and the robot appears in the camera frame, or its image is somehow overlaid on the visual display, then it's termed as a third-person perspective (3PP). This view can be fixed relative to the controlled robot, known as an egocentric 3PP view, in which case it follows the robot during its movements, placing the robot at the center of the visual field while the environment moves around it. Alternatively, it can be fixed in a distant environment, in which case the robot is observed moving within a fixed environment; this is called an allocentric or geocentric view.

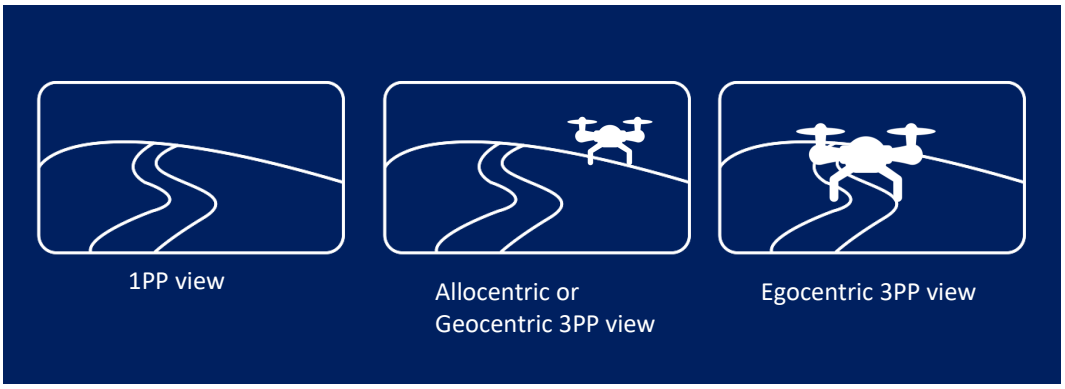

Figure 19: Visual perspectives in remote-controlled or virtual robot visualization

Depending on the task, specific perspectives and frames of reference will be more appropriate than others. A 3PP encompasses the robotic platform in the visual display. It not only increases the field of view but also provides additional information regarding the position and size of the robot relative to its environment. Studies demonstrate that in virtual reality, dynamic tasks involving operator movement or interaction with moving objects show that the third-person perspective (3PP) could significantly enhance user performance (Bhandari and O'Neill, 2020; Lee Pazuchanics, 2006; Salamin et al., 2006; Temma et al., 2019). Furthermore, a 3PP is integrated into the typical egocentric visualization when controlling UAVs and UGVs to enhance operators' spatial awareness (Erat et al., 2018; Kelly et al., 2011; Saakes et al., 2013; Saitoh et al., 2006; Temma et al., 2019; Thomason et al., 2017). On the other hand, the 1PP allows for better immersion in a virtual or remote environment as it provides a more natural view of the surroundings. This perspective was preferred when participants embodied a human avatar in virtual reality and needed to perform tasks requiring spatial awareness (Bhandari and O'Neill, 2020) or manual manipulation (Alonso et al., 2016; Salamin et al., 2006). However, in first-person view teleoperation, the camera's height is crucial. It has been shown that if the camera is positioned close to the operator's eye level, the perception of the environment is indeed more natural. Consequently, the

operator's perception of distances and, more precisely, the navigability of a robot through an opening becomes more accurate compared to when the camera is lower (Moore et al., 2009).

Map merging Even with the addition of a third-person perspective allowing for visual cues, the case of exploring unknown and/or hazardous environments, such as during search and rescue missions after a natural catastrophe, can prove to be complex and dangerous. A UAV or UGV may not know if its path could lead to a dead end. One solution could be the design of a map by multiple robotic agents. The fusion of visual information collected by one or more mobile robots to obtain a more comprehensive understanding of the environment to be explored could solve this problem (Marconi et al., 2012; Sujit and Beard, 2008).

Predictive displays Representing the visual impact of commands sent to the robot allows the operator to visualize the system's response before it occurs, thus avoiding potential collisions. Predictive displays are often used to mitigate the negative effects of time delay. For instance, Bejczy et al. (1990) proposed a teleoperation system for a robotic arm in the presence of time delay by real-time control of a graphical phantom robot whose movement on the monitor predicts the movement of the real robot. "*The movement of the real robot will then follow the movement of the phantom robot on the monitor with the communication delay involved in the task*." Krotkov et al. (1996) developed and validated a safeguarded teleoperation approach to time-delayed remote driving of lunar rovers (Figure 20). More recently, Prakash et al. (2023) proposed a perspective projection technique that provides operators with a forecasted video stream that replicates the future perspective of the vehicle's field of view, accounting for the delay present in the network. Their technique reduced the deviations and eliminated oscillations in the trajectory initially caused by time delay, bringing the human operator experience closer to that of a driver in a vehicle case.

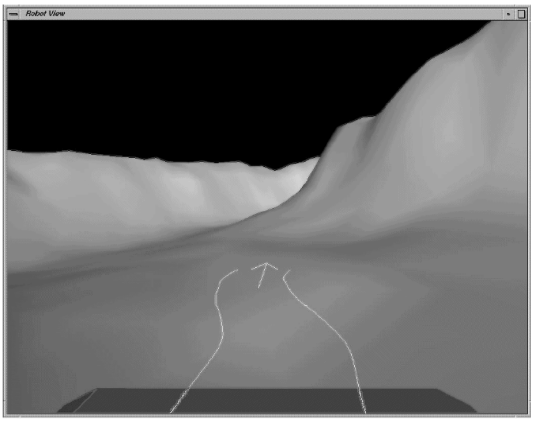

Figure 20: Safeguarded teleoperation for lunar rovers (Krotkov et al., 1996)

Attitude display The way to present the attitude information in a navigation task has consequences on pilots' spatial orientation. Müller et al. (2018) compared two different types of attitude indicators (AI): the moving-horizon (MH) format and the moving-aircraft (MA) format, corresponding to the standard AI used in Western and Soviet aviation, respectively (represented in Figure 21). They present different cognitive theories indicating that the MA format would be more intuitive and enhance spatial orientation during piloting. They also investigate to what extent the superiority of the MA format over the MH format in maintaining spatial orientation persists with current primary flight display technology. Their findings revealed that both novice and expert pilots demonstrated improved performance when using the MA AI format in tracking and recovery piloting exercises conducted in a PC-based simulator.

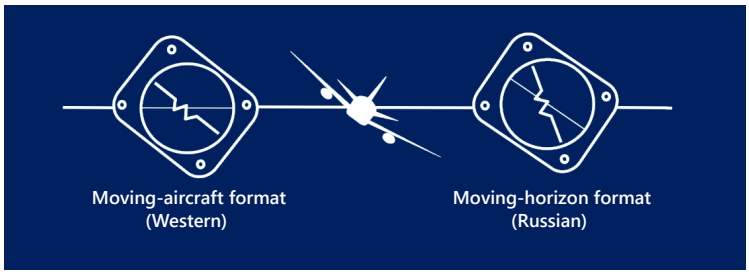

Figure 21: Attitude display type

Virtual reality There are several definitions of virtual reality (VR). Some definitions reduce VR to the use of a headset and interaction devices. However, VR extends far beyond this definition. If we take the definition of Fuchs (2006) translated from French, *"The purpose of VR is to enable a person (or several) to engage in sensorimotor and cognitive activity in an artificially created, digitally generated world, which can be imaginary, symbolic, or a simulation of certain aspects of the real world"*. When the environment in which a subject interacts is displayed on screens, such as a smartphone, tablet, or computer, it's referred to as non-immersive VR. Alternatively, if the environment is visualized through a headset, it's called immersive virtual reality. The headset allows the user to be fully immersed in the virtual world with a 360° view and to experience this simulated world as if it were real, creating a sense of presence. Augmented and mixed realities can be considered types of virtual reality. *Augmented reality* involves overlaying information in the form of text, images, or 3D models of objects onto the real environment. This information is typically triggered by certain elements in the real environment. The user can navigate the real environment but cannot interact with these virtual elements. Augmented reality can be visualized in both immersive and non-immersive ways. For example, in Pokémon Go, players navigate the real world to find virtual Pokémon that can be viewed through their smartphones. On the other hand, *mixed reality* allows interaction with the virtual environment overlaid onto the real environment and requires the use of immersive technologies. Examples of mixed re-

ality headsets include Magic Leap, Microsoft HoloLens 2, Meta Quest 3, and Varjo XR-4. These can be used by an architectural team to manipulate and modify a model of a real estate project or to visualize and manipulate a 3D reproduction of a human skeleton for educational purposes.

The applications of virtual reality for teleoperations are numerous. They allow operators to immerse themselves in the environment where the remotely controlled robot operates with high perceptual and situational awareness. VR enhances the operator's field of view (FOV), and when using immersive technologies, it also expands the Field of Regard (FOR). The FOV represents the size of the instantaneous visual field in degrees, while the FOR corresponds to the total surface of the visual field that can be seen by turning the head and moving the body, both significant factors in immersion (the objective level of sensory fidelity a VR system provides) and presence (the user's subjective psychological response to a VR system) (Bowman and McMahan, 2007; Meehan et al., 2002). VR also facilitates dialogue during teleoperation by providing additional spatial or visual information to reality. One technique of using VR for teleoperation is the reconstruction of a 3D environment on a screen (non-immersive VR). This can be achieved using information received from various sensors on the robot (Huber et al., 2009; Johnston et al., 2008). For instance, using the fusion of 3D data from laser scanners, 2D imagery from cameras, and the robot's odometry, Huber et al. (2009) created a photorealistic model of the remote environments, to which they added a virtual representation of the robot's state during navigation. The interface consists of a computer screen, steering wheel, and throttle. This method allows capturing and displaying data beyond the current sensor's FOV, thus increasing the FOV and observing the scene from alternate camera viewpoints (Figure 22).



Figure 22: Virtual 3PP Viewpoint. The 3PP is created using a synthetic representation of a remotely controlled vehicle in real-time, Huber et al. (2009)

Prexl et al. (2017) used the same methodology for controlling a UAV, but they displayed the 3D environment through a head-mounted display (the commercial VR equipment HTC Vive system), allowing the operator to teleoperate in a more immersive environment when performing search and rescue missions (immersive VR). Hong et al. (2017) used multiple onboard cameras of drones in a swarm to recreate a third-person view of the swarm in a visual search task and found that the third-person view provided better situational aware-

ness and search accuracy (Figure 23).

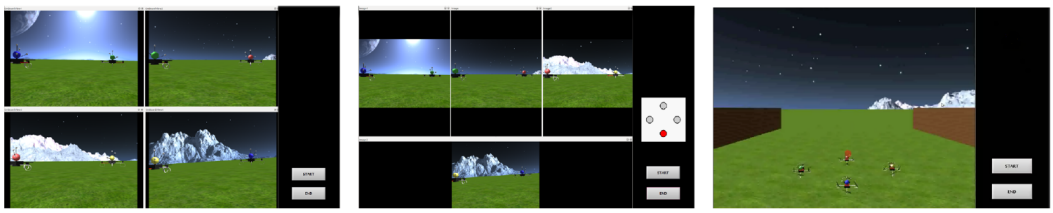

Figure 23: Global Visual feedback produced from drone swarm camera feed. "*Implemented visual feedback methods.* ***a*** *Real local view.* ***b*** *Fabricated global view.* ***c*** *Ideal global view.*" (Hong et al., 2017).

Multimodal teleoperation system (multi-sensory feedback or multimodal interfaces)

The actions between an operator and a remote robotic system are physically detached, and in standard teleoperation, the operator only relies on the visual feedback. Providing immersive solutions with visual and nonvisual feedback through displays and controls can improve teleoperation transparency and fidelity. Some examples of multimodal displays and inputs mentioned by Chen and Barnes (2014) include audio and tactile displays, which can serve as useful supplements to visual feedback to alert or direct attention. Haptic feedback helps to reflect the interaction forces between the remote robot and its environment onto the user's hand, notably used in teleoperation tasks conducted in microgravity (Riecke et al., 2016) (Figure 24).



Figure 24: Testing a haptic joystick aboard the ISS. Cosmonaut O. Kononenko performs experimental tasks using the DLR haptic joystick to control the ROKVISS robot at DLR Oberpfaffenhofen (Germany), (Riecke et al., 2016).

Additionally, haptic input controls, enable precise manipulation tasks such as telesurgery. Voice input controls prove valuable when manual input is impractical, such as when operating a moving vehicle or when both hands are occupied. Gesture input controls, encompassing the human body, arm and hand gestures, as well as facial expressions, offer an intuitive interface that can be utilized anywhere within the camera's field of view. Interestingly, Reveleau et al. (2015); Xavier et al. (2024) propose enhancing the visual display by presenting information from the remote environment that is not naturally visual, for example, by providing visual representations of forces and sounds captured from the real world on the teleoperation visual display (Figure 25). This multimodal feedback can be presented all together or chosen in accordance with what is pertinent to the task at hand. For instance, Triantafyllidis et al. (2020) showed that the *"combination of stereoscopic-vision with the virtual reality headset increased performance across all measurements by 40%, compared to monocular-vision from a generic display monitor. Besides, using haptic feedback improved outcomes by 10% and auditory feedback accounted for approximately 5% improvement"*.

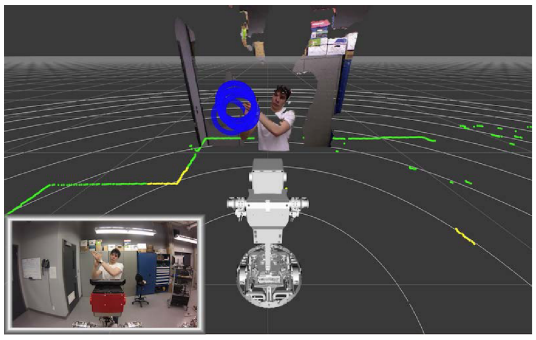

Figure 25: A visual representation of sounds from the remote environment proposed by Reveleau et al. (2015).

Physiological computing

The communication between a robotic system and a human operator can be considered asymmetric. The robotic system provides the human operator with a multitude of information regarding the robot's internal state, allowing the operator to adjust their commands accordingly. As we have seen in section 4.1, one of the issues in teleoperation that promotes human errors is related to the mental states of the human operator: their mental workload, fatigue, stress, motivation, attention, etc. One solution would be to make the H/R exchange more symmetrical by providing the robotic system with information about the operator's mental state. This way, the robotic system would be able to adapt to the internal state of the operator and thus meet their needs in real-time. This can be achieved with physiological computing (Fairclough, 2009) (Figure 26).

As presented in section 3, it is possible to obtain objective measures of operators' mental states using physiological markers from the brain, heart, and eye activity. Markers of

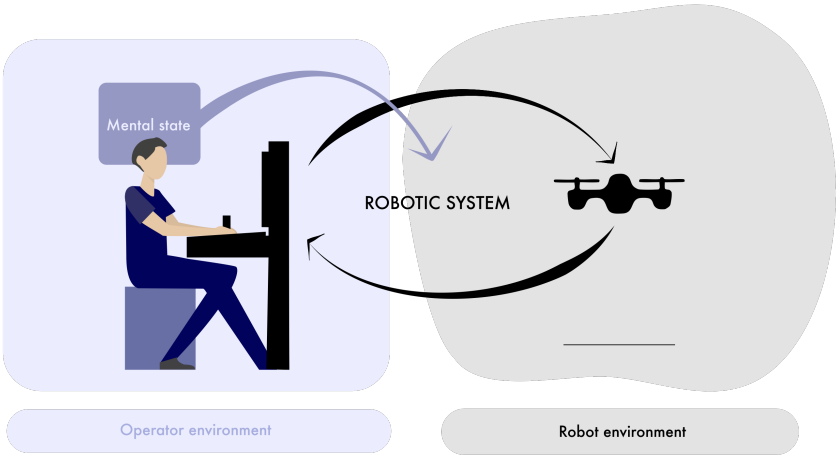

Figure 26: Representation of a physiological computing application for teleoperation

fatigue, inattention, mental overload, and stress can be identified in real-time, and the information is then communicated to the robotic system, which will take them into account and adjust the H/R interaction consequently (Roy et al., 2020; Singh et al., 2022).

For instance, results of Bailey et al. (2006) suggest that when performing monitoring and resource management tasks associated with a secondary tracking task that shifted between automatic and manual modes, brain-based adaptive automation systems (using EEG) enhanced participant SA while reducing mental workload relative to systems requiring user-initiated control. In Wilson et al. (2000) they showed that the automation of subtasks of the MATB (NASA Multiple Attribute Task Battery) when the operator was assessed to be in a state of mental “overload" reduced manual tracking and resource monitoring errors. There, the mental states and, more specifically, the mental workload of the operator were assessed using a combination of EEG, ECG, EOG measures, and respiration inputs.

Regarding motor activity, the electrical signals from the muscles operating the controller, measured via surface electromyography (sEMG), can be analyzed in real-time to provide additional information to the robotic system. They can indicate muscle fatigue, in which case a shared autonomous interface could reduce physical effort during teleoperations (Lin et al., 2020). It has the potential to mitigate the effects of time delay by commanding the remote robot to follow the predicted command extracted from the sEMG signal so that it is "ahead in time" from the command sent by the controller (Prokopiou et al., 1999). Moreover, it can enhance coordination and movement fluidity in teleoperation tasks. For instance, Yang et al. (2018) proposed a novel learning method for teleoperating a remote robot. In a drawing task, the sEMG signal is utilized to detect the operator’s muscle activation as they manipulate the haptic device to adapt to external environments. Muscle activation is recorded, analyzed, and integrated into the robotic system’s learning algorithm, allowing it to naturally adjust its trajectory and stiffness to the external environ-

ment. Additionally, the sEMG signal offers a simple and cost-effective means to discern the intended movement of the operator. Thus, sEMG signals from the muscles of the shoulder and/or elbow joints can be used to predict the corresponding joint angles and the force exerted by the user on the environment and to control a robotic arm/hand system in a 6D Cartesian space (Artemiadis and Kyriakopoulos, 2006; Meeker and Ciocarlie, 2019; Vogel et al., 2011), as well as during arms control in a virtual environment or an anthropomorphic telemanipulator (Suryanarayanan and Reddy, 1997).

5 | Chapter conclusion

Teleoperation definition Teleoperation is an operational method that enhances human capabilities remotely while ensuring worker safety. It utilizes a robotic platform to access environments that are inaccessible or too dangerous for humans, and to perform complex manipulation tasks. The control of the remote robot is carried out through an interface and a controller. The robot executes commands sent by the operator and, in return, provides visual and non-visual feedback (e.g., haptic feedback) about the remote environment and its state via the interface.

Fields of application The first manipulators appeared in the 1940s for handling radioactive materials. Thanks to recent technological advancements, many fields such as the military, aerospace, medical, and civil sectors have found significant interest in using such systems. To meet the growing and specific demands of these various sectors, designers must create efficient robotic platforms and user-friendly interfaces tailored to teleoperation contexts to optimize human-robot team performance.

Assessing teleoperation system effectiveness Evaluating the effectiveness of teleoperation systems is crucial for designing the optimal systems of tomorrow. Assessing these systems requires more than just measuring the efficiency of the robotic platform alone. A key determinant of the success of a teleoperation mission is the quality of interaction between the human and the robot. This is referred to as the usability evaluation of the system, a term used in HRI that encompasses both operator performance and experience. The measures found in the literature are often behavioral metrics specific to the tasks to be performed during the mission (perception, navigation, manipulation, social interaction, management). These measures reflect the success of various tasks during the mission, such as task completion time, the number of errors made, etc. In addition, subjective measures are also considered. These assess different aspects that can impact teleoperation performance, such as the operator's situational awareness, workload, telepresence, and tele-embodiment, all of which can be evaluated through questionnaires. These questionnaires can be supplemented with physiological measures to objectively assess the operator's mental state, possibly in real time and without interruption.

Teleoperation challenges and proposed solutions Improving the usability of teleoperation systems involves diagnosing and estimating the challenges operators may face. The main challenges reported in the literature can be classified into four key dimensions: the individual characteristics of the operator (who), the nature of the task to be performed (what), the robotic system used (control interface and the robot) (how), as well as both operational and control base environments (wherefrom). Solutions have already been proposed to address these identified issues and ensure good operational performance. Among

the proposed improved interfaces, different types of viewing modes and display types can be found, such as perspective changes, increased FOV, or even virtual reality. Another innovative proposal is to provide immersive solutions with visual and non-visual feedback through displays and controls to improve teleoperation transparency and fidelity. The robot can also adapt to the operator's mental state in real-time via physiological computing.

The case of teleoperation from dynamic environments The growing expansion of teleoperation applications leads to a diversification of environments and situations that operators may encounter. Among the recent application cases mentioned in this chapter, we observe that operators may, in certain cases, control a robot aboard a moving vehicle. As we have seen in the section presenting the various challenges in teleoperation found in the literature, only one review (Chen et al., 2007) mentions vehicle movements as a potential challenge for teleoperation tasks. The studies it cites show a decrease in performance during tasks involving interaction with a computer screen interface, but not during actual or simulated teleoperation tasks. Interestingly, one study does show decreased teleoperation performance, specifically difficulties for teleoperators in stabilizing their hands and movements. *"The FCS's Lead System Integrator performed a demonstration for the Concept and Technology Development phase, in which the operator teleoperated robotic vehicles from a moving command vehicle* (...). *The results showed that motion made all tasks harder, compared to an exercise in a simulated environment, and some tasks (e.g., editing plans and maps, and target acquisition) became almost impossible to perform due to the difficulty experienced by the operators in stabilizing their hand movements. The operators also tended to oversteer their robotic vehicles when their own vehicle was turning one way but the robot needed to turn the other way"* (Chen et al., 2007). It is interesting to note that this review also mentions some potential solutions to mitigate the effects of dynamic environments. The authors propose some interface improvements such as enlarging the keys, canceling vibration effects for joysticks, and replacing visual with audio input/output. They also cite a study of the US Army Research Laboratory (Hill and Tauson, 2005) that suggests several areas for improvement (not directly for teleoperation) related to the design of vehicles that reduce vibrations, training personnel for these dynamic contexts, and selecting personnel who are least affected during missions. Finally, they mention pharmaceuticals or other medical devices to deal with motion sickness.

This chapter reveals that, despite the emerging applications, the impact of dynamic environments—particularly vehicle movements (excluding vibrations)—on teleoperation is an emerging issue that the HRI community has barely investigated. Consequently, aside from some general recommendations, to the best of our knowledge, no adapted teleoperation interface has been tested or proposed for these dynamic teleoperation contexts. In the following chapter, we will examine, based on the existing literature, whether a dynamic environment could impact teleoperation efficiency and operator experience.

II. Teleoperating from dynamic environments

The growth of teleoperation applications leads to diversifying environments and situations that operators encounter. While traditionally confined to a control base where the operator sits statically in front of a computer, nowadays, these professionals may find themselves teleoperating from dynamic environments, such as moving vehicles. For instance, recent military projects such as the FCAS (Future Combat Air System) use MUM-T (Manned-Unmanned Teaming), which aims to pair manned and unmanned vehicles to perform specific missions and tasks. The emergence of these new contexts of dynamic teleoperation raises the question of their possible impact on teleoperation system usability.

The objective of this chapter is to examine whether a dynamic environment could impact teleoperation. We will begin by describing the specificities of such an environment and the gravito-inertial changes it induces. Then, we will present the sensory systems involved in the perception of movement and, consequently, these gravito-inertial changes. To our knowledge, no study has directly explored the impact of dynamic environments on teleoperation. Therefore, we will examine existing studies on the impact of gravito-inertial changes on various human abilities, ranging from perception to motor control, as well as their influence on motion sickness symptoms. We will also discuss studies conducted in more operational situations, analyzing the impact of vehicle movement on interaction performance with a computer system. We will address the effects of stimulus-response spatial (in)compatibility, which we believe to be an important factor in the impact of vehicle movement on teleoperation performance. Finally, we will conclude this chapter by presenting the research objectives of this thesis and describe the experimental protocols aimed at filling the gaps identified in the literature on the impact of dynamic environments on teleoperation.

6 | Dynamic environments characteristics

In the case of teleoperation from a control base located in an office, the operator is in a stable environment; the forces acting on their body include Earth's gravity, those generated by their movements, and those applied by the interface. These forces are, therefore, constant and predictable as they result from the actions deliberately performed by the operator.

6.1 | Changes in gravity orientation and intensity

Gravity is the attractive force that acts between all bodies with mass. Newton first formulated it as follows:

Two point masses, m and m', located at a distance r from each other, attract each other with a force directed along the line joining them, a force whose magnitude is proportional to the masses and inversely proportional to the square of the distance: $G = 6.672 \times 10^{-11}\, Nm^2kg^{-2}$ *is the gravitational constant* [Larousse, 2024].

Human evolution has aligned our head and body axes with Earth's gravity and adapted us to its intensity. However, individuals aboard a moving vehicle may find themselves in situations where their body and head are no longer aligned with gravity. Additionally, operators may experience accelerations that increase or decrease the intensity of the gravitational force they feel, creating variable load factors. In aerodynamics, the load factor (or g force) is a measure that describes the force applied to the aircraft structure and its pilot and crew (Park et al., 2015). It is expressed in g and represents the ratio between the apparent weight (as experienced, due to gravity and inertial forces) and the actual weight (due to gravity). When the load factor is positive, it means that the acceleration forces are directed downwards, thus increasing the sensation of weight. This typically occurs during rapid climbs or sharp turns. For example, a load factor of +2 g indicates that the pilot and crew feel a force equivalent to twice their average weight. A load factor close to 0g occurs during rapid descents or maneuvers where the aircraft follows a parabolic trajectory, creating a temporary state of weightlessness. This method is also used to evaluate the effects of space weightlessness Shelhamer (2016) and for astronaut training (European Space Agency (ESA) (n.d.)).

6.2 | Additional inertial forces

In addition to variations in gravitational force, inertial effects or forces can occur and fluctuate during such a mission. Inertial forces, also known as pseudo-forces, act on masses when observed from a non-inertial reference frame. For example, imagine a person throwing a ball straight ahead from a carousel rotating clockwise: they will observe the ball being strongly deflected to the left. However, for an external observer, the ball follows a straight

trajectory while the subject rotates. This example illustrates the **Coriolis force** (Bles, 1998). This force applies to segments and objects in motion within a rotating environment, acting perpendicular to the direction of movement. In a pointing task on a screen aboard a moving vehicle, this force could similarly deflect the arm's movement to some degree in the opposite direction of the vehicle's rotation. On the other hand, **centrifugal force** applies to the entire body of individuals or objects in rotation, tending to push them away from the center of rotation. Centrifugal force pins us against the door of our car when the driver makes a tight turn.

Therefore, when an operator teleoperates from a dynamic environment, such as aboard a helicopter, boat, or mobile control base, in addition to the vibrations emitted by the vehicle, the accelerations, decelerations, and inclinations induced by the vehicle's movement alter the forces applied to the operator (Figure 27). Changes in gravitational force can be experienced in both intensity and direction (e.g., during turns and up and down accelerations), and new inertial forces may act on the operator's body. Moreover, unlike a static control base, these gravitational-inertial changes fluctuate and are unpredictable.

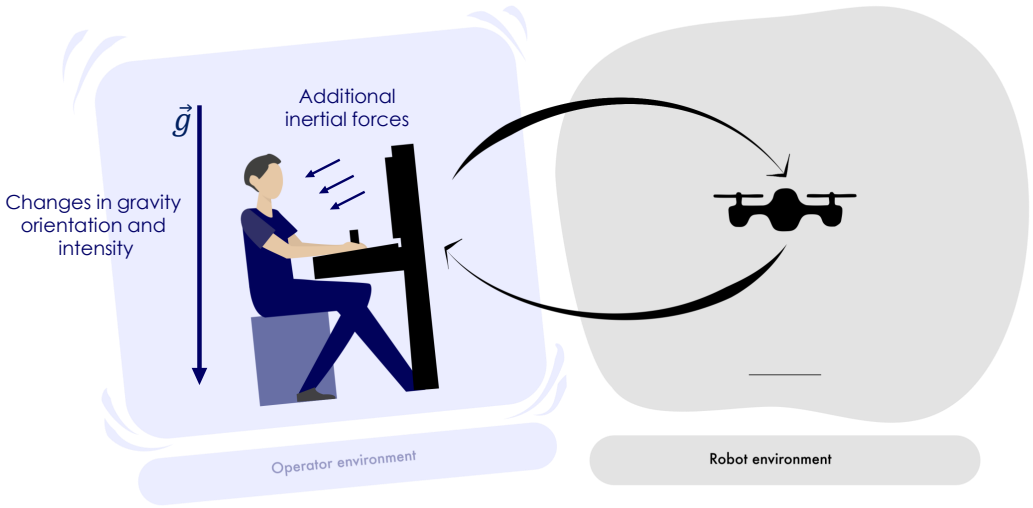

Figure 27: Teleoperation dynamic environment characteristics.

Can these modified and unpredictable force environments impact the performance of perception or control of the remote robot? Before addressing this question, a brief consideration of the physiology and cognition behind the sense of human movement will help understand the challenges operators face in these dynamic conditions.

7 | Sense of Motion

Since Antiquity, five common senses have been recognized: vision, hearing, taste, smell, and touch, facilitated by various sensors such as our eyes, ears, mouth, nose, and skin. However, there are lesser-known but physiologically essential senses, such as verticality, equilibrium, proprioception, and the sense of motion. These processes involve determining the direction and intensity of gravitational and other inertial forces acting on the body, as well as assessing the position of our body and limbs relative to this geocentric reference. Berthoz refers to these processes as the *"sense of movement"* or *"kinesthesia"*, which he considers a sixth sense. Unlike the other senses, this one involves multiple sensors, including the vestibular and somatosensory systems, as well as the visual system (Berthoz, 1997).

7.1 | The sensors

The anatomical descriptions and functions of the sensors presented below are drawn from and summarized based on the book Purves et al. (2019).

The visual system

The sense of vision remains central to our perceptual abilities and interactions with the environment due to the quantity and quality of information it provides about the world. To achieve this, it detects, translates, and interprets information about light within the visible spectrum to construct an image and a mental model of the surrounding environment.

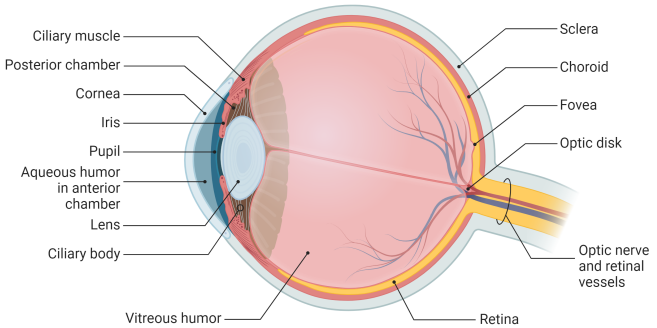

Figure 28: Anatomy of the Human Eye. Source: Biorender.

Structure of the Eye The eye is the central organ of vision (Figure 28). Light passes through the cornea and lens, which adjusts its curvature to focus the image on the retina

(Figure 29), a nerve layer lined with photoreceptors (cones and rods). These receptors convert light into nerve signals, sent to the brain via the optic nerve, where they are processed in various visual areas, enabling the perception of colors, shapes, and movement. The pathway involved in visual perception is known as the geniculo-striate pathway. Stimuli are initially analyzed in the primary visual area V1 and then in the secondary visual areas in the occipital lobe before continuing through two major pathways: the ventral and dorsal streams. The ventral stream extends into the temporal lobe and involves the detailed vision of shapes, colors, and textures for object recognition. The dorsal stream, on the other hand, extends into the parietal lobe and is involved in spatial aspects of vision, including motion detection and the recognition of positional relationships between objects in the visual scene.

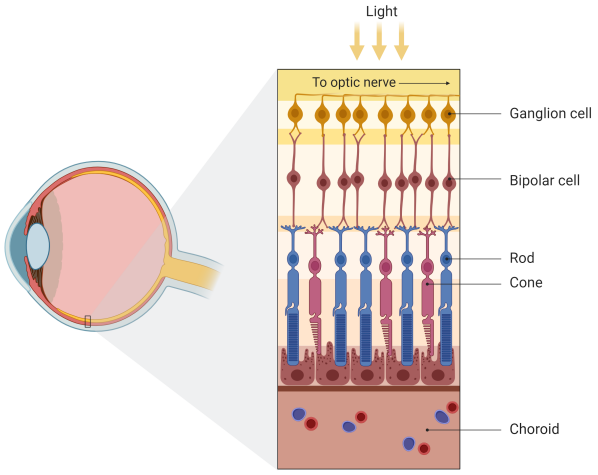

Figure 29: Structure of the retina. Source: Biorender.

The vestibular system

The sensors of the vestibular system are located in a structure of the inner ear known as the labyrinth. The labyrinth consists of two main components: the bony labyrinth and the membranous labyrinth (Figure 30).

The bony labyrinth is encased within the temporal bone and is filled with perilymph, a fluid with a composition similar to cerebrospinal fluid. It includes the vestibule and three semicircular canals, each oriented in one of the three spatial planes. The membranous labyrinth is situated within the cavities of the bony labyrinth. It is composed of a membranous structure lined with epithelium and is filled with endolymph.

The membranous labyrinth includes the utricle and saccule (otolithic organs) and the anterior, horizontal, and posterior semicircular canals. The endolymphatic duct and sac

supply endolymph to these structures. The semicircular canals open into the utricle at regions known as ampullae.

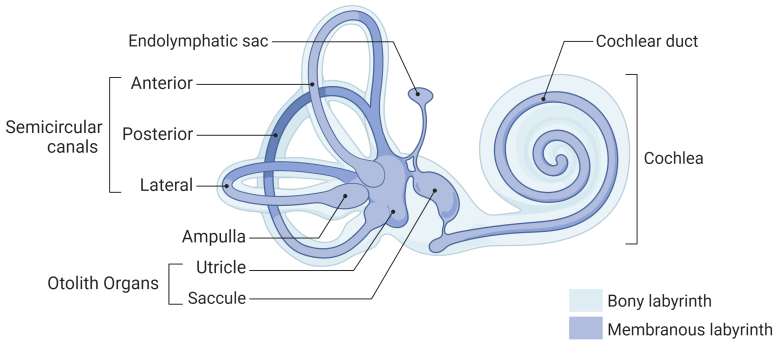

Figure 30: Anatomy of the Inner Ear. Source: Biorender.

The central organs of the vestibular system are the otolithic organs and the semicircular canals. In both of these organs, the transduction of movements into neural signals is accomplished by specialized sensory cells called hair cells. As their name indicates, these cells are equipped with numerous stereocilia arranged in increasing length towards the longest stereocilium, known as the kinocilium. The arrangement of these cilia has a specific orientation, with each hair cell having a polarity axis relative to the kinocilium. This orientation allows the hair cells to respond differently based on the direction of the ciliary deflection. The hair cells synapse with bipolar ganglion neurons, which transmit vestibular information to the vestibular nuclei in the brainstem via the vestibulocochlear nerve.

Otolithic organs and linear acceleration perception

Structure The otolithic organs consist of two parts: the utricle and the saccule. The structure comprising the hair cells in these organs is called the macula. The cilia of the hair cells in the macula extend into a gelatinous substance known as the otolithic membrane. This membrane is covered with calcium carbonate crystals called otoliths.

Functioning When the head moves linearly, the otoliths, due to their mass, cause displacement of the otolithic membrane. The cilia embedded in this membrane bend or flex in response. Depending on the direction and extent of ciliary bending, the hair cells in the macula generate a neural signal. The mass of the otolithic membrane relative to the surrounding endolymph causes the cilia weighted by the otoliths to shift transiently during linear accelerations or continuously during head tilts (Figure 31). Due to their orientation—vertical for the saccular macula and horizontal for the utricular macula—these organs detect vertical and horizontal linear accelerations, respectively. The cilia of the sac-

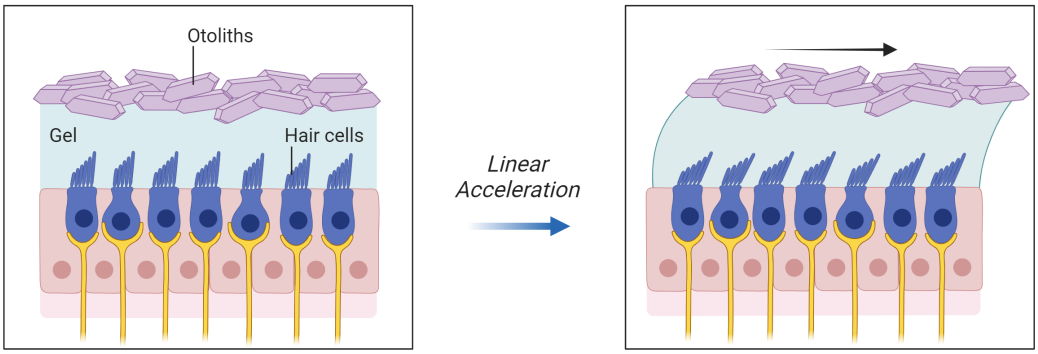

Figure 31: The macula of the otolith organs. Source: Biorender.

cule are sensitive to gravity and are thus constantly oriented downward, leading some to describe the saccule as the body's plumb line.

Semicircular canals and angular acceleration perception

Structure The semicircular canals consist of three semicircular canals and three ampullae. The canals are filled with a fluid called endolymph and are oriented perpendicular to each other: the horizontal (or lateral) canal, the superior (or anterior) canal, and the posterior canal. The ampullae are the receptors of this subsystem. They are located at the base of each canal and, similar to the otolithic organs, are composed of a structure of sensory hair cells known as the crista ampullaris. The hair cells in the crista ampullaris are embedded in a gelatinous structure called the cupula, which obstructs the ampulla cavity and forms a flexible barrier that the endolymph circulating in the semicircular canals cannot penetrate.

Detection of angular acceleration During head rotation, the canals move through space, but the endolymph inside the canals remains stationary. Similarly to what happens when you rotate a glass of water around its central axis, the glass turns without moving the liquid, which remains fixed. Consequently, relative to the head, this causes the endolymph to move within the canal, deforming the cupula and bending the stereocilia (Figure32). Depending on the inclination of the stereocilia towards the longer (kinocilia) or shorter hair cells, the hair cells will either become hyperpolarized (increased firing rate of this canal's nerve signals) or depolarized (decreased firing rate of this canal's nerve signals). This differential response allows each semicircular canal to determine whether the head tilt occurs in the plane of that specific canal.

Integration of signals from the three canals Each canal is sensitive to rotations in its plane. The horizontal canal detects rotations around a vertical axis (e.g., turning the head

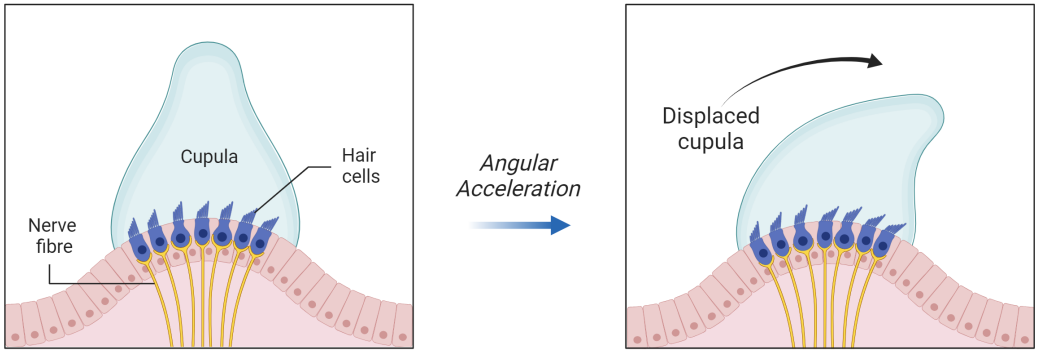

Figure 32: The crista ampullaris of the semicircular canals. Source: Biorender.

left or right). The superior canal detects rotations around a horizontal axis (e.g., nodding the head "yes"). The posterior canal detects rotations around another horizontal axis (e.g., tilting the head towards the shoulders). During complex head movements, the brain combines signals from the stimulated canals to determine the precise direction of the tilt.

Integration of signals from all six canals for 3D perception The right and left vestibular organs are symmetrically positioned in the inner ears. The left horizontal canal mirrors the right horizontal canal. The left superior canal mirrors the right posterior canal. The right superior canal mirrors the left posterior canal. Thus, each canal has its counterpart positioned in mirror symmetry in the opposite inner ear. The horizontal canals work in pairs to encode head rotations in three dimensions. When a rotation occurs, the canals on one side are excited while their counterparts on the opposite side are inhibited. This coordinated and opposing response allows the brain to precisely detect the direction and magnitude of rotational movements by integrating signals from all six semicircular canals.

The somatosensory system

The somatosensory system is responsible for the perception of bodily sensations, such as touch, temperature, pain, and proprioception (the perception of the position and movement of body parts). This complex system involves a series of sensory receptors, neural pathways, and specific regions of the brain. These sensations are enabled by a wide variety of sensory receptors located throughout most of the human body. We can identify the cutaneous and proprioceptive mechanoreceptors that will be presented below, as well as thermoreceptors and nociceptors, which detect temperature and pain but will not be covered here.

Mechanoreceptors Mechanoreceptors are sensory cells sensitive to mechanical deformations. They respond to stimuli such as touch, vibration, pressure, as well as muscle stretch

and joint movement. Mechanoreceptors are classified into cutaneous and visceral types, which are incidentally stimulated by gravity and other inertial forces, and proprioceptive mechanoreceptors located in muscles and tendons, which will be discussed later.

Cutaneous mechanoreceptors Cutaneous mechanoreceptors are sensitive to mechanical deformations of the skin caused by contact with objects. The five main types are Meissner's corpuscles, Merkel's discs, Pacinian corpuscles, Ruffini corpuscles, and free nerve endings. Each type is located at different depths in the skin, transmits different types of information, and has distinct functional characteristics (Figure 33).

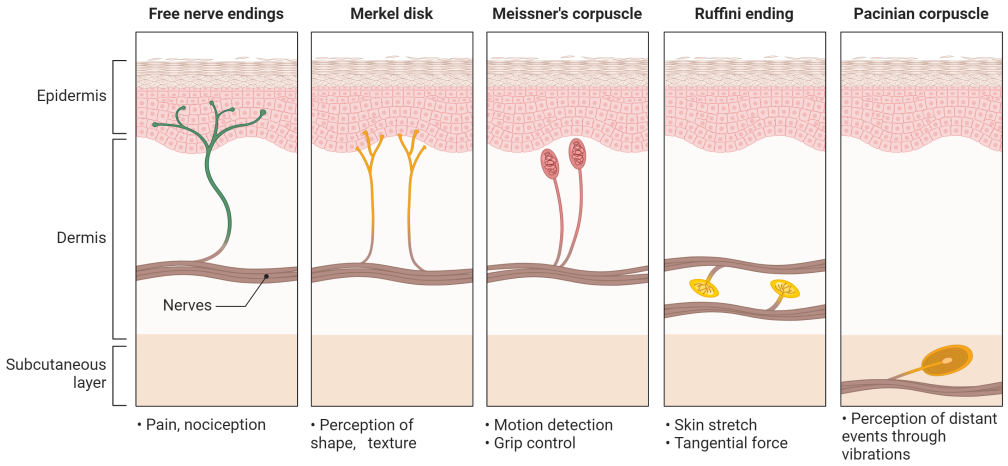

Figure 33: Types of cutaneous mechanoreceptors. Source: Biorender.

Visceral receptors In addition, mechanoreceptors present in the viscera signal distension, and nociceptors may indicate damage, such as inflammation of an organ. These mechanoreceptors contribute to interoception and provide information about the body's position relative to the vertical (Mittelstaedt, 1996; Trousselard et al., 2004).

Proprioceptive mechanoreceptors Proprioceptive mechanoreceptors are sensitive to muscle stretch and contraction. They detect changes in muscle length and tension, as well as the rate of these changes, allowing the CNS to regulate and coordinate body movements. The main proprioceptive mechanoreceptors are the muscle spindles and the Golgi tendon organs.

Muscle Spindles Muscle spindles are specialized structures located within skeletal muscles (Figure 34). They detect changes in muscle length and the rate of these changes. Within the muscle, certain muscle fibers (intrafusal fibers) are enclosed in a connective capsule

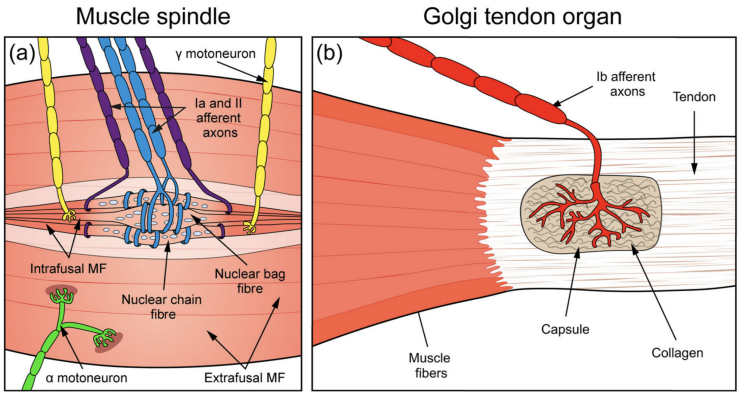

Figure 34: Proprioceptor organs in skeletal muscles *"(a) Schematic drawing of a muscle spindle. The muscle spindle contains nuclear bag and nuclear chain intrafusal fibers. Both of them are innervated by Ia afferent axons (blue) that form annulospiral endings in the equatorial region. Some intrafusal muscle fibers are also innervated by II afferent axons (purple). Additionally, efferent -motoneurons (yellow) establish motor contacts on the intrafusal muscle fibers in the muscle spindle's polar regions. Outside the muscle spindle, an -motoneuron (green) establishes synaptic contacts with the extrafusal muscle fibers. (b) Schematic drawing of a Golgi tendon organ. This organ is located at the muscle–tendon junction and is filled with collagen bundles. A single large Ib afferent axon (red) enters the Golgi tendon organ and after splitting into several branches, nerve terminals establish contact with the collagen fibers of the Golgi tendon organ."* (Blumer et al., 2024)

known as a muscle spindle. During muscle stretching, the intrafusal fibers also stretch, which activates the surrounding nerve endings and generates a receptor potential. If this receptor potential exceeds a certain threshold, an action potential is transmitted to the CNS via the Ia sensory neuron, reflecting the amplitude of the stretch based on its frequency.

Golgi Tendon Organs Golgi tendon organs are located at the musculotendinous junctions of tendons (Figure 34). This organ consists of a network of collagen fibers surrounded by sensory nerve endings. When the muscle contracts, stretching at the musculotendinous junction causes the collagen fibers in the Golgi organ to come closer together, deforming the sensory nerve endings and generating a receptor potential. Similar to muscle spindles, if this receptor potential exceeds a threshold, it generates an action potential in the afferent Ib neuron, which is then transmitted to the CNS.

7.2 | Perception of gravito-inertial forces and sensorimotor implications

Motion perception relies on information from multiple sensory systems. Collectively, the visual, vestibular, and somatosensory systems work together to provide a comprehensive understanding of vertical orientation, self-motion, and the position and movement of our limbs.

7.2.1 | Sense of Verticality

The perception and estimation of verticality refer to "*the human ability to explicitly perceive the direction of verticality, to create a mental representation of verticality from this perception, and to use this representation explicitly or implicitly to navigate (postural control) or orient a part of their spatial environment*" (translated from French, Barra and Pérennou (2013)). Visual invariants in the environment, such as the orientation of trees, buildings, the horizon, and celestial bodies like the sun and stars, provide information about the direction of the gravitational vector. The otolithic organs within the vestibular system act as a biological "plumb line," indicating the position of the head relative to gravity. Additionally, inputs from the somatosensory system—derived from muscle, joint, skin, and visceral receptors—contribute to the estimation of the gravitational vector (Barra and Pérennou, 2013; Goldberg, 2012).

The vestibular system cannot distinguish between the force of gravity and the linear forces that act upon the otoliths. They only provide a combined vector of gravito-inertial forces. How is the direction of gravity alone defined? The frequency segregation hypothesis suggests that this separation is achieved by distinguishing between the slowly varying component, representing gravity, and the rapidly varying component, representing inertial acceleration. By combining this estimate with semicircular canal inputs, which detect head rotation, it may be possible to obtain an accurate estimate of head orientation in space (Zupan et al., 2000).

However, sensory systems measuring gravity are still imperfect and may provide ambiguous information. To overcome this, our nervous system also relies on an internal representation of how gravity affects our environment, body, and movements, in addition to direct graviceptive information (Kawato, 1999; Merfeld et al., 1999). For instance, an internal model of gravity and linear accelerations could help resolve ambiguous gravito-inertial signals perceived by the vestibular system (Merfeld et al., 1999).

7.2.2 | Proprioception

Proprioception refers to the perception of the spatial position and movement of our limbs and other body parts. This sensation largely relies on visual feedback about the limbs (Bagesteiro et al., 2006; Graziano, 1999). Additionally, proprioceptive mechanoreceptors in the somatosensory system, located in muscles, joints, and tendons, play a crucial role. These sensory cells are sensitive to mechanical deformations, such as muscle stretch, tendon tension, and joint movement, allowing for estimating the position and movement of various body parts. The vestibular system also provides information about the head position and movement. These vestibular signals are integrated with visual and somatosensory inputs to maintain an accurate perception of our body's position and movement in space. (Purves et al., 2019)

7.2.3 | Self-motion perception

Several sensory cues contribute to self-motion estimation in space (read Greenlee et al. (2016) for a review). The visual system uses the displacement of images on the retina to perceive movement. Visual cues to self-motion include the displacement of visual features relative to the observer and the pattern created by the motion of the image of the environment on the retina, referred to as optic flow. This pattern is often represented by a set of motion vectors with a direction defined by the focus of expansion and an intensity represented by the length of the vector. Optic flow thus contains information about the direction and magnitude of linear or rotational movement. In addition, the otolith organs and semicircular canals of the vestibular system provide information regarding the linear and rotational accelerations of the head in space. When the motion is self-induced, proprioceptive mechanoreceptors of the somatosensory system contribute; for example, it is possible to estimate the distance walked via the mechanoreceptors present in the muscles, joints, and tendons (Harrison et al., 2013).

7.2.4 | Internal model for perception and motor control

One of the key theories in neuroscience and computational cognitive science is the hypothesis that the CNS employs internal models to plan, control, and learn movements (read Wolpert and Ghahramani (2000) for a review). These models, which represent physical laws and body biomechanics internally, are integrated within neural circuits and refined through experience. They enable the modeling and anticipation of interactions between our sensory systems, motor systems, and the physical world (Fiehler et al., 2019). This theory is particularly useful for explaining sensorimotor changes in modified force fields (for instance, Crevecoeur et al. (2010)).

According to the internal models hypothesis (Wolpert and Ghahramani, 2000; Wolpert and Kawato, 1998), the CNS uses an inverse model to compute the motor commands needed to execute a given movement, based on the current state of the system and the desired outcome. Simultaneously, a predictive (or forward) model anticipates the sensory consequences of these commands (also called efference copy). During movement, the CNS compares actual sensory feedback with the predictions of the forward model. If a discrepancy arises, the movement is adjusted, and the error is incorporated into the motor command to update the internal model and facilitate learning (Figure 35, Wolpert and Ghahramani (2000)). For instance, when reaching to grab a glass, the inverse model calculates the necessary motor commands, while the predictive model anticipates the expected sensory feedback. If a perturbation occurs during the action (e.g., a modified force field), the motor command generated by the internal model may become unsuitable. This creates a mismatch between the model's estimated hand position and its actual position, resulting in a sensorimotor discrepancy. The error is then corrected, and the internal model is adjusted to the new force field to improve accuracy in subsequent attempts.

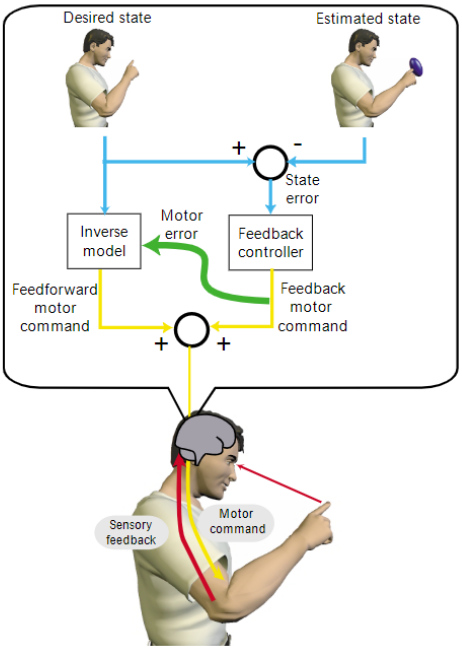

Figure 35: A schematic representation of feedback-error learning, from Wolpert and Ghahramani (2000)

For instance, predictive mechanisms such as the motor efference copy and internal models have been shown to participate in the estimation of self-motion (Rineau et al., 2023), as well as in tactile sensitivity (Arikan et al., 2024; Fuehrer et al., 2022). Furthermore, as noted by Kawato (1999), the internal representation of gravity can be classified as an inverse model of physical laws, utilizing acceleration and gravity as inputs. The CNS uses this representation to resolve gravitational-inertial ambiguities perceived by the vestibular system, thereby enabling accurate perception and interaction with the environment, as well as effective planning and control of movements (read White et al. (2020) for a review on *The gravitational imprint on sensorimotor planning and control*).

7.3 | Implication for dynamic environment teleoperation

Therefore, movement information from the visual, vestibular, and somatosensory systems is complementary and contributes to proprioception, self-motion, vertical estimation, and motor control. Most of the time, the information provided by these different sensory systems is congruent; they provide information about the same event. For example, consider a pilot in flight. The pilot experiences gravito-inertial changes resulting from their actions (anticipated by the motor efference copy). When a command is given to descend the aircraft, the decrease in gravitational force on the otoliths causes the otolithic crystals to rise, and the decrease in the pilot's weight alters the stimulation of various mechanoreceptors

in the somatosensory system. This is accompanied by the visual shift of the horizon line moving upward in the pilot's field of view. All sensory information is then congruent, indicating the aircraft's descent and matching the motor efference copy created during the motor command.

Now, imagine a teleoperator using an immersive interface (such as a First-Person View (FPV) headset) on board the aircraft during the descent. Their gravito-inertial sensory systems will detect the aircraft's descent while simultaneously visually perceiving the distant environment through the interface, reflecting the movements of the teleoperated robot. In this case, there is a discrepancy between what is perceived vestibularly and somatosensorially and what is observed through the interface. The teleoperator could experience an intersensory conflict regarding proprioception, self-motion, or vertical estimation.

Furthermore, according to the internal model hypothesis (Wolpert and Ghahramani, 2000; Wolpert and Kawato, 1998), humans rely on pre-established internal models of gravity and motor commands shaped by prior experiences. In dynamic environments where force fields are constantly changing, these motor commands can become inappropriate for new contexts. A key aspect of the internal model theory is its gradual adaptation to novel environments. However, in scenarios such as moving vehicles, where the force field is continuously shifting and unpredictable, the adaptive capabilities of internal models are constrained, complicating the process of motor control.

Do these gravito-inertial changes and potential intersensory conflicts induced by dynamic environments affect teleoperation? In other words, do they impact the performance of robot perception and control, as well as the experience and satisfaction of operators? These are the questions we will address in the following section by drawing from the existing literature on the subject.

8 | Impact of gravito-intertial changes on cognition

To the best of our knowledge, there are still very few studies to date that address the impact of dynamic environments caused by moving vehicles on teleoperation performance per se. However, existing literature can shed light on the impact of dynamic environments and altered force fields on the perceptual and motor abilities involved in teleoperation tasks. Indeed, the neuroscience literature seeking to generate models and explain the functioning of the sensorimotor system in its natural environment proposes several experimental protocols and methods that induce gravito-inertial modifications and intersensory conflicts to study perceptual and motor adaptation to these changes (See reviews on the role of gravity in perception and motor control, e.g.: Bock (1998); Jörges and López-Moliner (2017); White et al. (2020)).

Sensorimotor and cognitive abilities can be assessed through several paradigms. Here, we will primarily focus on experimental studies with potential applications for teleoperation tasks. For instance, pointing and manual tracking tasks could potentially be trans-

ferable to robot control, while perception tasks, such as perceiving verticality, self motion, distances, and objects, could be applied to the perception of interface parameters, the distant environment, as well as the robot itself and its movements. Additionally, we will present several operational studies from the military and autonomous vehicle domains, which have evaluated the effect of real or simulated vehicle movement on the sensorimotor and cognitive performance of operators carrying out tasks involving a computer interface onboard the vehicle.

8.1 | Experimental approach

Several experimental methods exist to modify the perception of gravity and induce intersensory conflicts. The most commonly used are described in the following subsections.

Microgravity and hypergravity

Perceived gravity intensity can be modified by exposing participants to an environment in a free fall, such as aboard the International Space Station or during parabolic flight campaigns (Shelhamer, 2016). Underwater immersion provides a way to specifically study the somatosensory system's involvement in gravity perception, as the lack of somatosensory signals produces a floating sensation similar to that of microgravity (Weber et al., 2018). Gravity intensity can also be modulated by exposing participants to a hypergravity environment, which can be achieved through short- or long-arm centrifuges (Clark et al., 2015) or by increasing the load factor experienced by passengers on an airplane (during the ascending phase of parabolic flights or tight turns) (Clément, 2018).

Head and body tilt

Perceived gravity direction can be modified by tilting the participants' bodies and/or heads relative to gravity along various body axes and at different angles of inclination (Dyde et al., 2006; Wade, 1968). This can be achieved by positioning the participant prone or supine, for instance. Furthermore, the use of a tilting motion platform can be advantageous because it allows for a wider range of inclination angles and exposes participants to dynamic changes in gravity direction when the platform is in motion. Note that microgravity and hypergravity environments automatically induce intersensory conflict because the gravitational signals are not accompanied by the usual visual cues of freefall or acceleration (optic flow). To induce intersensory conflict during body tilting, experimental tasks must be conducted using an immersive visual environment, such as a head-mounted display (HMD).

Vestibular Stimulation

Another way to induce intersensory conflict is by adding noise to the signal provided by the vestibular system through vestibular stimulation, either galvanic or caloric (Volkening et al., 2014). Galvanic vestibular stimulation (GVS) is a non-invasive method that affects the input to the vestibular system. Electrodes placed behind the ears deliver controlled low electrical currents, creating sensations of movement. Caloric vestibular stimulation (CVS) involves introducing air or water at different temperatures into the ears, inducing a sensation of movement towards the ear where a warm temperature has been applied.

Induction of external forces

Experimental approaches also exist that create an altered dynamic environment to assess adaptation and learning processes in motor control (Lackner and DiZio, 2005). Disruptions can be induced by mechanical or inertial forces. Mechanical forces are applied through contact between a robotic arm and the limb performing the movement. Inertial forces, on the other hand, do not require physical contact and are induced by rotation in a centrifuge. To assess the effect of centrifugal forces, participants can be positioned at a distance from the axis of rotation. To evaluate the effect of a force that induces a mechanical disturbance of the arm without affecting the vestibular system, Coriolis forces can be induced solely on the limb by placing the subject on the rotation axis of the centrifuge with constant rotation. Additionally, the effects of broader gravito-inertial changes can be assessed using motion platforms, which allow for the combination of body tilting and light inertial forces.

8.2 | Perception

Verticality and gravity

Human evolution has resulted in an alignment of our head and body axes to the Earth's gravitational forces. Literature shows that as soon as humans are no longer aligned with the vertical, their cognitive processes are less effective. For instance, in an upright position, without any visual information from the environment, humans are still able to align a luminous rod with the vertical (subjective visual vertical test, SVV) with an accuracy of less than 1 degree (Tabak et al., 1997). However, as soon as they are tilted, they experience a perception bias. The SVV shifts towards the tilt/body axis for large tilts (underestimation of a large tilt, >45°–60°, Aubert or A-effect (Aubert, 1861)) or in the opposite direction (overestimation of a small tilt, Müller or E-effect, (Muller, 1916)). The larger the tilt, the more they reorient the SVV toward our body axis. Mittelstaedt (1983) suggested that the A-effect is linked to the idiotropic vector, which represents the internal bias that tends to assume that both the head and vertical axes should be aligned. Also, as in the SVV test, when per-

forming the subjective haptic vertical test (SHV), tilted humans struggle to manually orient a real rod in the direction of gravity (Fraser et al., 2015; Schuler et al., 2010).

Furthermore, when visual cues informing of the direction of the vertical are available and presented aligned with the retina, while the body is tilted, graviceptive inputs are incongruent. The vestibular, somatosensorial, and visual inputs provide different estimates of the direction of the vertical, leading to intersensorial conflicts. Surprisingly, in these situations, the "right way up" does not correspond to the physical vertical, to the SVV, nor the body axis. Instead, it corresponds to another orientation that Dyde et al. (2006) calls the Perceptual Uprigh, which is defined as the orientation in which objects are most easily recognized and would correspond to the sum of body, gravity, and visual background orientation vectors. Graviceptive cues have also been found to contribute to modeling the effects of gravity on a moving target. Therefore, the perception of an object's motion and acceleration (Miwa et al., 2019) as well as its interception timing, can be affected when the observer's body is tilted (La Scaleia et al., 2019).

The perception and reproduction of the horizontal orientations are also affected by body tilt. When upright, the oblique effect reflects our ability to estimate both vertical and horizontal orientations. However, when the body is tilted, the oblique effect disappears (Lipshits and McIntyre, 1999), and interestingly it has been shown in another study that once again the subject's subjective vertical appears to be processed with better accuracy and precision than all other orientations (Luyat and Gentaz, 2002). Contrary to body tilt, microgravity did not impact the oblique effect observed on Earth. In both micro- and normogravity, vertical and horizontal orientations are always preferred in comparison with oblique orientations (Lipshits and McIntyre, 1999). However, Villard et al. (2005) observed a decrease in geometric illusions composed of horizontal and vertical lines (such as the reversed-T, Müller-Lyer, Ponzo, and Hering illusions) in microgravity compared to normogravity, indicating that these illusions *"are not just due to optical effects, but also depend on the integration of other sensory signals, including gravity-based and somatosensory cues"* (Villard et al., 2005).

Self motion perception

Self-motion perception enables to dynamically perceive changes in our position in space and time, while also allowing us to adjust our movements and behavior in response to the external world (Rineau et al., 2023).

Research shows that intersensory conflicts, caused by the modulation of vestibular (and somatosensory) or visual information, can lead to sensory illusions of movement or distort the perception of visual optic flow. Incongruent graviceptive cues induced by a tilted body position while wearing an HMD impacted optic flow perception in McManus and Harris (2023). Furthermore, incongruent motion cues seem to also influence self-motion perception. For instance, incongruent motion cues provided by optic flow can create the illusion

of self-motion while the observer is stationary, known as Vection (Palmisano et al., 2015). However, incongruent motion cues provided by vestibular cues seem to provide inconsistent results. For instance, in Edwards et al. (2010) incongruent motion cues provided by moving the participants' bodies decreased optic flow sensitivity, whereas in Shirai and Ichihara (2012) it increased optic flow sensitivity, and in Holten and MacNeilage (2018) no congruency effect was observed.

Furthermore, in a review, Rineau et al. (2023), highlights the importance of the notion of agency in self-motion perception and its technological implications. It demonstrates that agentive (i.e., voluntary) movements alter perceptual mechanisms, specifically the reweighting of sensory inputs. The author explains this by suggesting that voluntary movement engages the intention/action/effect loop, which predicts the sensory consequences of the action. This prediction of sensory consequences would then facilitate the integration of relevant sensory information.

3D perception

3D perception refers to the ability to perceive one's environment in three dimensions: width, height, and depth of various elements within the space. In microgravity, visual and haptic perception of 3D objects deteriorates (Clément et al., 2008; Morfoisse et al., 2024). For instance, in Clément et al. (2008), subjects perceived a normal cube to be taller, thinner, and shallower in microgravity compared to normal gravity. A distance perception test confirmed that subjects underestimated the distance of objects in the depth plane in microgravity. Clément et al. (2016) found that gravity also impacted the estimation of egocentric distance (the distance between oneself and an object placed between 2 and 6 meters). The results showed that egocentric distances were perceived as shorter in hypergravity and longer in microgravity.

3D perception also seems to be impacted by tilted body positions. For instance, objects appear larger or closer when lying down (Kim et al., 2022); authors suggested that this effect *"may provide survival benefits in such a vulnerable position"*. Additionally, Morfoisse et al. (2024) showed that when upright, subjects naturally tend to visually underestimate an object's depth and overestimate depth when exploring the object haptically. When tilted, the same distortions occur if responses are aligned with the subject; however, these distortions are very different if they are aligned with gravity. This indicates that the perception of 3D objects, both visually and haptically, differs depending on whether the subject is upright or lying down.

8.3 | Cognition

Different experimental environments, such as neutral buoyancy, vestibular stimulation, and microgravity, have been shown to impair what can be referred to as higher cognitive functions. For instance, Dalecki et al. (2012) demonstrated that underwater (at a depth

of 5 meters), cognitive performance in tasks such as sustained attention deteriorated. According to the authors, these effects might be caused by tactile stimulation and cardiovascular changes induced by the higher ambient pressure, which could influence cognitive processing. Dilda et al. (2012) showed that degraded vestibular afferent inputs from GVS stimulation also negatively affected cognition, in particular, performance on tests requiring perspective-taking (egocentric mental transformations) and the *match to sample* test, which involves spatial memory. Lopez et al. (2012) indicated that CVS temporarily alters the body schema, such as the internal representation of hand size. Furthermore, microgravity environments have been shown to impair cognition (for instance, mental imagery) (read Grabherr and Mast (2010) for a small review).

8.4 | Motion sickness

Incongruent motion cues provided to the vestibular system are known to induce motion sickness symptoms. These symptoms can occur aboard moving vehicles such as airplanes, cars, or boats. They vary widely and can include general discomfort, drowsiness, dizziness, headaches, nausea, vomiting, and malaise, among others. Additionally, sensitivity to motion sickness varies greatly between individuals (read Bertolini and Straumann (2016) for a review on motion sickness).

Iskander et al. (2019) presents the different types of motion sickness that can occur in connection with autonomous vehicles, categorizing them into three types: motion sickness induced by vision, that caused by Coriolis and pseudo-Coriolis effects, and finally, that primarily induced by physical movements. (1) Vision-induced motion sickness is triggered by the observation of a large and immersive moving visual field. This type of motion sickness can generate an illusion of vection, meaning an illusion of self-motion while the person is stationary. This vection may be accompanied by classic motion sickness symptoms, such as nausea and dizziness. (2) Motion sickness caused by Coriolis and pseudo-Coriolis effects occurs when a head tilt is combined with body rotation (Coriolis effect) or with visually perceived rotation without actual physical rotation (pseudo-Coriolis effect). In the case of the pseudo-Coriolis effect, the rotation of the visual scene around the subject creates a sensation of self-rotation, triggering similar symptoms of motion sickness. (3) Motion sickness induced by physical movements refers to the real movements of a vehicle, such as those experienced during seasickness, airsickness, or in land transportation.

Game designers using virtual reality and head-mounted displays (HMDs) are very familiar with the symptoms of vision-induced motion sickness, also known as cybersickness. Indeed, these types of symptoms can also occur during the use of HMDs in virtual reality environments. In this case, a visual-vestibular conflict arises when the user navigates a virtual world while remaining physically stationary. The optical flow information provided by the HMD conflicts with the normal sensory expectations, producing cybersickness symptoms similar to those of motion sickness (read Davis et al. (2014) for a review on

cybersickness).

Furthermore, upon arrival in space, between 60% to 80% of astronauts experience varying degrees of space motion sickness or space adaptation syndrome (SAS) (Lackner and DiZio, 2006). Common symptoms include disorientation, nausea, vomiting, and drowsiness. While these symptoms usually subside after a few days, some astronauts never fully adapt, and symptoms may persist for the duration of their mission. Even among those who eventually overcome SAS, challenges with spatial orientation continue to persist when their eyes are closed. Another possible explanation for these symptoms, according to the internal model hypothesis, is that the syndrome results from a mismatch between the expected sensory input and the actual sensory input experienced in microgravity (Carriot et al., 2021).

8.5 | Motor control

When performing a movement to reach a target in our environment, our CNS takes into account the spatial relationship between the target and our position. If this spatial relationship changes during the movement (due to a change in the position of the target, the body, or the hand), our CNS must adapt and correct the movement to reach the target, considering these changes. To study motor adaptation to these changes, several experimental paradigms exist. Here are examples of studies evaluating the effect of modified force fields and intersensory conflicts on sensorimotor performance, primarily involving hand and arm movements. The results of manual tracking and pointing task paradigms are presented below, as they seem relevant here. Indeed, their results can potentially transfer to teleoperation performance, as they are similar to the direct manual control of a robot via a controller or even interaction with a button interface.

Manual tracking

The manual tracking paradigm involves moving a target along a prescribed trajectory. Most often, the task requires aligning a cursor with a target that may be either stationary or moving. The cursor can either have variable inertia or correspond directly to the input from the controller used for the task. Performance measures for tracking are then based on the distance between the target's position and the cursor's position throughout the task. Additional kinematic measures are used to describe the motion of the cursor during the task, such as speed, acceleration, and jerk (the rate of change of acceleration with respect to time).

Numerous studies have shown altered manual tracking performance when exposed to modified force fields (for instance, Bock et al. (2001, 2003); Hagengruber et al. (2021); Manzey et al. (1993); Mierau and Girgenrath (2010); Weber et al. (2016)).

Let's take a closer look at the example from Weber et al. (2016), which evaluated manual tracking performance using a 2D joystick under various force field conditions. Notably,

their study introduced a new manual tracking paradigm to make their results transferable to robotic control tasks, such as robotic arms or docking maneuvers that astronauts must perform during space missions. Their task involved a zero-order (or position) control tracking task, meaning that the output's position directly corresponds to the input position, and the target has to be matched along a pre-defined path and with constant speed. The task was performed on Earth with an extra arm weight and under real (ISS) and simulated (underwater) microgravity conditions.

They measured the mean distance between the cursor and the target, as well as the mean, peak, and standard deviation of speed and acceleration. They hypothesized that movement acceleration and acceleration variance would decrease with added arm weight compared to normal conditions, that tracking error would increase in weightlessness (underwater and ISS conditions) compared to normal conditions and that corrective movement would lead to higher levels of acceleration and speed variance in weightlessness compared to normal conditions. The results showed that subjects with added arm weight were able to maintain a level of tracking performance by reducing their arm accelerations and acceleration variance. Consequently, movements were smoother and slower. Underwater, subjects experienced a drop in performance, associated with increased mean and peak speeds, as well as peak and standard deviation of acceleration. Results from an astronaut performing the task physically also showed increases in all measured parameters, confirming their initial hypotheses.

Pointing movements

Other paradigms are the pointing movements, which involve approaching a prescribed endpoint. These tasks can be performed on a screen by pointing a cursor to a target or in 3D by making a pointing movement with the hand or arm to a physical target, sometimes involving movement of the torso. Many studies observe an altered performance in pointing movements when exposed to modified force fields or visuo-vestibular conflicts.

For example, studies inducing GVS have shown that a change in vestibular input at the start of arm movements toward memorized visual targets (performed later in complete darkness) leads to a deviation of the hand's trajectory toward the side of the anode (Bresciani et al., 2002). According to the authors, this deviation aims to compensate for the perceived body movement caused by the GVS. Additionally, Mars et al. (2003) demonstrated that GVS also affects the final position of pointing movements toward a memorized target, requiring arm-trunk coordination during trunk-assisted reaching movements.

Results are also controversial regarding the adaptation of actions when the body or head is misaligned with respect to gravity. Some studies describe poorer performance in hand and arm pointing movements (Scotto Di Cesare et al., 2014; Smetanin and Popov, 1997; Tagliabue et al., 2013), or in estimating the position of their hand (Gallagher et al., 2021). On the other hand, some studies observed no significant differences between upright

and tilted body positions (Bourdin et al., 2001b; Fouque et al., 1999).

In Holden et al. (2023), gravitational transitions during a 6-month mission were shown to impact fine motor skills during interaction with a touchscreen. The authors conducted a tablet-based test battery of four fine motor tasks: Pointing, Dragging, Shape Tracing, and Pinch-Rotate, in pre-flight, in-flight, and post-flight phases. Their results showed no change in performance during the flight but noted decrements in performance at gravitational transition points: the first week in space and the first month after landing. Interestingly, Bringoux et al. (2020) and Mechtcheriakov et al. (2002) observed rapid and effective adaptation to microgravity. In microgravity, movements tend to be smooth and maintain accuracy according to Mechtcheriakov et al. (2002). Additionally, in a task evaluating sensorimotor flexibility in space and on Earth (Bringoux et al., 2020), participants had to perform a target-jumping pointing task, requiring movement correction during the action. The results showed similar performance and kinematic profiles in both gravity conditions; however, a difference was observed in the neuromuscular strategy used. Contrary to previous studies, these data highlight a rapid and effective adaptation to the altered force field environment.

In a more operational study, Moore et al. (2011) assessed the performance of 11 pilots during Space Shuttle landing simulations in the vertical motion simulator at NASA Ames Research Center, Moffett Field, CA. The study demonstrated that GVS altered sensorimotor performance during the simulated Shuttle landings. Landing speed increased and reached the upper limit of the target range. Hard landings, with landing speeds in the "red" (unacceptable) range, nearly doubled, accompanied by an increase in the number of crashes. These results were similar to those observed under real mission conditions, they indicate that GVS is an effective analog for the performance decrements observed in Shuttle pilots after spaceflight and show that incongruent vestibular graviceptive cues can impact performance in tasks close to operational reality.

Some studies suggest that these performance decrements during exposure to microgravity might be because the CNS uses an internal model of gravity that does not immediately update itself in space. This has been shown during capture movements (McIntyre et al., 2001) or grip force adjustment tasks (Crevecoeur et al., 2009, 2010). For instance, McIntyre et al. (2001) showed that astronauts initiated capture movements earlier in $0g$ than in $1g$ because they did not anticipate that the ball would not accelerate in microgravity. This demonstrates that the brain uses an internal model of gravity to complement sensory information when estimating contact time. Adaptation occurred only after the 9th day. Bock (1998) explained that the problems with sensorimotor coordination in tracking and pointing tasks in weightlessness and the discrepancies between studies are because adaptation to weightlessness can be very resource-demanding. Humans use motor programs that depend on gravity; in microgravity, these programs are no longer suitable. The subject then experiences a sensorimotor discordance (a difference between the input and output of the movement), which requires modifying these programs to be effective in the new force

field. Brock compares this active adaptation mechanism to those used when learning new motor skills, which are also very resource-intensive. Furthermore, he explains the differences in results between studies by the fact that the tasks performed may require different levels of cognitive resources, thus affecting task performance differently.

Furthermore, studies on adaptation to Coriolis forces allow for the investigation of sensorimotor adaptation to an external inertial force that does not require mechanical contact with the limb performing the task. The protocols involve placing subjects in a rotating centrifuge at a constant speed. The subjects' heads are positioned on the centrifuge's axis of rotation, and no visual cues indicate its rotation. This way, the Coriolis effect is only felt on the participant's arm. In Lackner and Dizio (1994), participants were required to reach memorized visual targets as accurately as possible without visual feedback on the moving limb. Initially, subjects exhibited significant deviations in movement curvature and endpoint towards the direction of the Coriolis force. However, subjects rapidly adapted to the Coriolis force so that their reaching movements straightened out and aligned more closely with the target within about ten attempts. Later, Lackner and Dizio (1998) showed that if Coriolis forces are accompanied by centrifugal force (when subjects are placed farther from the rotation axis), participants could no longer adapt their movements. Later, the study by Bourdin et al. (2001a) confirmed that adaptation in such disturbed gravito-inertial force fields occurred when visual feedback of the moving arm was allowed during the movement. Note that, in these studies, the Coriolis force was continuous and remained constant across trials.

9 | Impact of vehicle motion

Beyond the impact of vibrations, to the best of our knowledge, very little research focuses on the impact of a moving vehicle on sensorimotor performance when controlling a remote robot. Initial investigations in this domain primarily stem from military studies on the impact of vehicle motion on soldiers' performance during tasks requiring interaction with military interfaces such as battle management systems. Later, studies on autonomous vehicle motions emerged.

9.1 | The effect of vibration

For a long time, extensive research has focused on the impacts of mechanical vibrations on human performance in a working environment. These vibrations can occur in moving vehicles, particularly in military settings and near heavy industrial machinery. Many studies have reported decreased visual acuity and motor performance (Conway et al., 2007; Grether, 1971; Nakashima, 2005). However, central neuronal processes such as reaction time, monitoring, and pattern recognition appear to be highly resistant to the effects of vibrations (Grether, 1971). Today in France, daily exposure to vibrations is regulated by

labor law, which recommends not exceeding 1.15 m/s^2 for vibrations transmitted to the entire body, for instance (Article R4443-1, Légifrance (2008)).

9.2 | Military studies

In 1988, the U.S. Army delved into human factors issues for future Manned Ground Vehicles (MGVs) and conducted field exercises to enhance command and control (C2) operations in future environments. A mobile tactical operations center offers reduced vulnerability and operational adaptability advantages. Consequently, efforts were made to develop future MGVs to be fast, lightweight, and fully operational while in motion. This required reduced crew members and increased individual responsibility, presenting a challenge to developers to design interfaces that enable soldiers to carry out their missions without becoming overwhelmed (McDowell et al., 2007). The U.S. Army Research Laboratory (ARL) subsequently investigated the impact of an off-road moving C2 vehicle on soldiers' cognitive performances in computer-based tasks compared to stationary vehicles. The findings indicated decreased accuracy (7–46% degradation) and slower performance (7–40% decrease). These impairments affected various cognitive areas, including time-sharing, selective attention, inductive reasoning, memorization, and spatial orientation (Schipani, 1998). In other studies on the same subject, soldiers showed diminished results in the Delta cognitive battery test and increased motion sickness when in a moving C2 vehicle (Cowings, 1999), higher workload, and impaired performance during tasks that required users to enter information in the BSM, but no impairment during tasks that required information extraction (for instance, reading) (Goode et al., 2012).

Furthermore, vehicle simulator studies have shown that motion reduces the speed and accuracy (McDowell et al., 2005) and increases task completion times and both subjective and physiological workload (Salmon et al., 2011) during manual reaching tasks on touch screens. In 2007, McDowell from the U.S. Army Laboratories identified *vehicle motion effects* as one of the four core issues that must be addressed to enable effective FCS MGV designs to ensure soldier security. They mentioned that their motion effect challenge includes the *understandable presentation of information, implementation of controls minimally influenced by vehicle motion, and the reduction of Soldier disorientation and motion sickness* (McDowell et al. (2007), Figure 36).

9.3 | Autonomous vehicles studies

With the introduction of autonomous vehicles, the same question arises. Autonomous vehicles allow passengers to engage in tasks unrelated to driving and interact with various interfaces during vehicle motion, such as touch screens or Augmented, Virtual, and Mixed Reality. The predominant concern highlighted in the literature revolves around the motion sickness passengers may experience when visually focused on a task that does not align

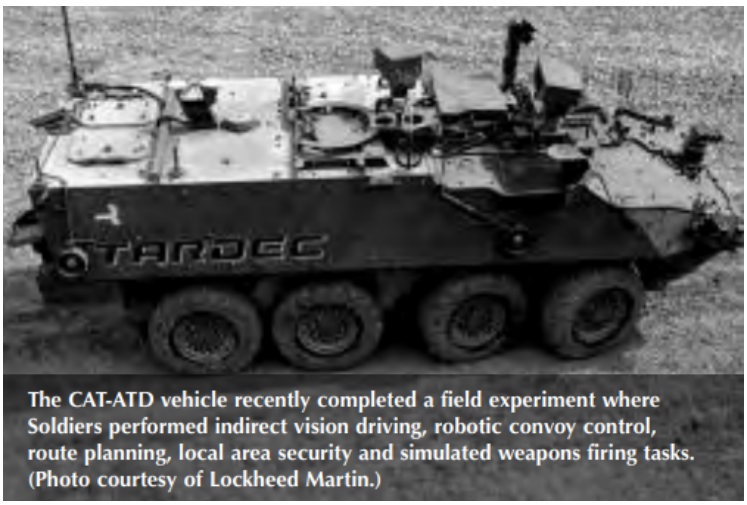

Figure 36: Indirect vision driving of the CAT-ATD vehicle, from (McDowell et al., 2007).

with vehicular movements. This creates sensory conflicts and may cause inconvenient symptoms for the passenger (Iskander et al., 2019; McGill et al., 2017, 2020). Other studies have also noted that vehicle movements can influence the quality of interaction with the tactile interface. For instance, simulating vehicle motion can impact gaze and gesture behavior, making interaction with the interface more challenging and requiring participants to exert more effort to compensate for it (Colley et al., 2021). Real vehicle motions have also been reported to affect information input on a tactile interface; the more intense the movements, the greater the distances between the desired input and the actual input (Ahmad et al., 2015).

According to some authors, decreases in operator performance are primarily attributed to vehicle vibrations during motion (Schipani, 1998), which are known to degrade sensory input, reducing both visual acuity and motor task performance. In Cowings (1999), the authors attribute these performance declines to motion sickness symptoms caused by intersensory conflicts, particularly when the operator is focused on a visual display inside a moving vehicle. They also mention a drop in motivation and concentration due to distractions caused by vehicle movements. The study by Salmon et al. (2011) partially links the decline in performance to an increase in mental workload for the operator. Furthermore, McDowell et al. (2005) explain the degradation in operator movements by a lack of anticipation, noting that these results align with cognitive theories, which suggest that the ability to predict environmental changes is crucial for planning and controlling movements. They also highlight that the vehicle's enclosure creates intersensory conflict and reduces predictability, as participants could not see the path taken by the simulated vehicle. Consequently, the unpredictability of vehicle movements leads to inadequate operator responses due to the inability to anticipate external disturbances.

10 | Spatial Compatibility Effect

As explained in Section 4.3, a challenge faced by teleoperators, as highlighted in the literature (Murphy and Schreckenghost, 2013; Steinfeld et al., 2006), relates to the compatibility between the provided information (stimuli) and the response executed by the operator when interacting with the teleoperation system. Here, we will present these concepts in more depth and explain why we believe that stimulus-response compatibility concepts can affect teleoperators in the studied context, i.e., from dynamic environments.

10.1 | Stimulus-Response compatibility effect

In a sensorimotor task, information (Stimulus) is perceived and processed, followed by a decision regarding the appropriate motor response for the given situation (Response). Work by Fitts and Seeger (1953) highlighted that certain Stimulus/Response pairs are more compatible than others, thus influencing performance in sensorimotor tasks. Fitts defines a compatible SR complex as *"to the extent that the ensemble of stimulus and response combinations comprising the task results in a high rate of information transfer"*, where a high rate of information transfer means that information is transferred and processed quickly and accurately. He adds that *"the degree of compatibility is at a maximum when recoding processes are at a minimum"*, where recoding processes refer to the cognitive processes that handle stimulus information and generate a motor response. In other words, during a task that requires processing information (stimulus) to produce a motor response (response), the degree of compatibility between the stimulus and response depends on the amount of information processing (transformation or recoding) required to generate the response. More processing indicates lower compatibility, while minimal processing reflects high compatibility.

Several effects illustrate the compatibility between stimulus and response. The Stroop effect (Stroop, 1935), for instance, occurs when a stimulus has two characteristics, one congruent with the task and the other incongruent, such as naming the ink color of a word that represents a different color (e.g., the word "green" written in red). The Flanker effect (Eriksen and Eriksen, 1974), on the other hand, arises when distractors surround the stimulus. The stimulus again contains two characteristics, some congruent and others incongruent with the task, such as identifying a central "H" surrounded by distracting "S" letters. The effect relevant to our research is the spatial compatibility effect between stimulus and response, or the Simon effect, which we present in more detail below.

10.2 | Spatial compatibility

Building on Fitts' studies, Simon and his colleagues demonstrated that the compatibility between stimulus and response can be based on the spatial characteristics/attributes of both the stimulus and the response (see Hommel (2011) for an overview).

Impact of the stimulus' irrelevant directional cues on reaction time For example, Simon and his colleagues showed that when a stimulus contains directional information that is incompatible with the response but irrelevant to the task, performance is degraded. In their first study, Simon and Rudell (1967) had participants press a button positioned either on their left or right based on an auditory cue (the words "left" or "right"). These words could be presented through the left or right speaker of a headset. The results showed that the word's location affected sensorimotor performance, even though the location varied randomly and provided no relevant information for the task. When the words were presented on the same side as the required motor response (spatial compatibility), participants responded faster than when the words were presented on the opposite side (spatial incompatibility) (Simon and Rudell, 1967). To confirm that this incompatibility was not due to a semantic conflict (between the heard word and the stimulated ear) but rather a conflict between the stimulus and motor response, they repeated the experiment using tones instead of words and found the same results (Simon and Small Jr, 1969). Moreover, the spatial compatibility effect persists even when participants cross their arms, indicating that it is not the hand's lateralization but the actual spatial relationship between the stimulus and the response that matters (Simon et al., 1970). This compatibility effect was also observed when participants could not see their arms and hands, meaning that it can occur even when the positions of the responding limbs are specified solely by kinesthetic cues (a situation that could arise in immersive teleoperation) (Wallace, 1972).

Impact of an irrelevant distractor's directional cues on reaction time In these studies, the directional characteristics were carried directly by the stimulus itself. Interestingly, Simon and Craft (1970) demonstrated that when an auditory distractor is presented simultaneously with a visual stimulus, the directional cues of the distractor can influence visuomotor performance. Participants were instructed to press a button on their left or right based on the position of one of two LED lights that turned on. Alongside the visual stimulus, an irrelevant auditory tone (distractor) was presented either to the left or right ear (monaural stimulus) or to both ears simultaneously (binaural stimulus). Participants reacted faster (choice reaction time) when the stimulus and distractor (carrying directional cues) were presented on the same side as the motor response. This finding suggests that the Simon spatial compatibility effect can occur even when directional cues are provided by a distractor in a different sensory modality than the one used for the task. Furthermore, the binaural stimulus served as a baseline, and the results showed that the monaural tone had a facilitative effect when spatially compatible and an inhibitory effect on visual reaction time when incompatible, compared to the binaural stimulus.

While, to our knowledge, no study has yet shown that a body movement can produce the same Simon effect as a sound presented in one ear during a visuomotor task (Simon and Craft, 1970), we are curious whether a similar spatial compatibility effect could impact teleoperation performance.

11 | Chapter conclusion and proposed experimental approach

11.1 | Chapter conclusion

Dynamic Environment Characteristics When an operator teleoperates from a dynamic environment, such as on board a helicopter, boat, or any other type of mobile control base, the accelerations and tilts induced by the vehicle's motion, in addition to its vibrations, modify the forces exerted on the operator. Variations in gravitational force can be felt both in intensity and direction, and new inertial forces may act on the operator's body. Unlike in a static control base, these gravito-inertial changes fluctuate and are hardly predictable.

The sense of movement The perception of movement is made possible by integrating information from various sensors. Together, and in a complementary manner, the visual, vestibular, and somatosensory systems contribute to estimating verticality, proprioception, self-motion, and movement control. Most of the time, the information provided by these sensory systems is congruent. However, on board a moving vehicle, the vestibular and somatosensory systems detect vehicle movements (tilts, accelerations, decelerations). A teleoperator controlling a remote robot via a visual interface could then experience intersensory conflicts regarding the perception of verticality, self-motion, and proprioception. Furthermore, according to the internal model hypothesis, movements are planned, controlled, and learned using internal models of physical laws and body biomechanics. These models, built and refined through experience, predict the sensory consequences of a movement. If a mismatch is perceived between predicted and actual sensory information, the internal model adjusts. On board a moving vehicle, the altered and constantly changing force fields would require continuously adapting these internal models.

Impact of the dynamic environment and its implications for teleoperation Studies on the effects of gravito-inertial modifications and visuo-vestibular intersensory conflicts show that body tilting, changes in load factor, inertial forces, and vestibular stimulations, which may induce visuo-vestibular conflicts, affect numerous human perceptual and motor capabilities. Table 3 summarizes the effects these gravito-inertial changes and intersensory conflicts can have on human cognitive abilities, as well as their implications and potential risks for teleoperation tasks. These studies highlight that not only perceptual abilities (such as proprioception, self-motion perception, verticality perception, and 3D perception) but also motor control abilities (e.g., pointing and manual tracking tasks, especially when using joysticks) can be impaired. Moreover, these conflicts are known to induce motion sickness symptoms.

Furthermore, the literature shows that certain stimulus/response pairs are more or less compatible, leading to faster and more accurate responses or, conversely, slower and more error-prone responses in sensorimotor tasks. For instance, the Simon effect demonstrates that spatial attributes of a stimulus, even if irrelevant, can influence performance. The question remains whether this effect applies to teleoperation scenarios, where an operator may experience movement in one direction while having to control or monitor a robot moving in another direction.

If these effects extend beyond experimental settings and transfer to teleoperation from dynamic environments, it could disrupt how the operator perceives the remote environment and the objects within it, as well as how they control the robot. This would result in decreased operator performance, reduced satisfaction, and ultimately, lower usability of teleoperation systems. However, as presented in Chapter 1, despite the growing applications of teleoperation in dynamic environments, the HRI community has scarcely studied the impact of the operator's body movement on the usability of teleoperation systems. Therefore, to our knowledge, aside from general recommendations, no teleoperation interface specifically adapted to these dynamic contexts has been tested or proposed.

Impacted Aspect	Reference	Potential implications for teleoperation tasks
Perceptual upright	Aubert (1861); Dyde et al. (2006); Mittelstaedt (1983); Muller (1916); Tabak et al. (1997)	Misperception of verticality, leading to spatial disorientation during monitoring and/or positioning errors and incorrect robot movements during direct control.
Subjective haptic vertical	Fraser et al. (2015); Schuler et al. (2010)	Misperception of limb position in space (proprioception), leading to inappropriate commands through the controller, causing manipulation or navigation errors.
Orientation perception	Lipshits and McIntyre (1999); Luyat and Gentaz (2002); Villard et al. (2005)	Misperception of the environment's orientation (objects, horizon, vertical), leading to misreading instruments (e.g., attitude indicator).
Optic flow perception	Edwards et al. (2010); McManus and Harris (2023); Shirai and Ichihara (2012)	Misperception of the robot's movement (e.g., distance traveled, speed, and tilt) in the remote environment, potentially causing navigation errors or collisions.
3D Perception	Clément et al. (2008); Kim et al. (2022); Morfoisse et al. (2024)	Misjudgment of the distant environment's object sizes, distances, and dimensions, potentially causing collisions during navigation, excessive grip pressure (risk of damage) during manipulation, or inappropriate social interactions (e.g., collisions with humans).
Manual tracking	Bock et al. (2001, 2003); Hagengruber et al. (2021); Manzey et al. (1993); Mierau and Girgenrath (2010); Weber et al. (2016)	Precision and trajectory errors, leading to deviations from the intended path, impacting task efficiency and safety in tasks requiring robot control along a predefined trajectory.
Pointing task (using a joystick, hand, or arm)	Ahmad et al. (2015); Bresciani et al. (2002); Colley et al. (2021); Holden et al. (2023); Mars et al. (2003); McDowell et al. (2005); Moore et al. (2011); Scotto Di Cesare et al. (2014); Smetanin and Popov (1997); Tagliabue et al. (2013)	Precision errors in reaching target points in both the operator's environment (manual interaction with the teleoperation interface) and the remote environment (task requiring the approach of a precise target in the distant environment).
Motion sickness	Cowings (1999); Iskander et al. (2019); McDowell et al. (2007); McGill et al. (2017, 2020)	Distraction, discomfort, potentially impacting operator effectiveness.
Mental workload and general cognition	Cowings (1999); Dalecki et al. (2012); Dilda et al. (2012); Lopez et al. (2012); Schipani (1998)	Cognitive overload, performance decline, and increased error rates.

Table 3: Summary table of the effects of gravitational-inertial changes and intersensory conflicts that may impact human cognitive abilities, along with their potential implications and risks for teleoperation tasks.

11.2 | Research questions and experimental blocks

The objective of this thesis is twofold: to analyze whether a dynamic environment can impair teleoperation and to assess whether a teleoperation visualization interface could be adapted to these dynamic teleoperation contexts. Our research questions are therefore:

1. Does the operator's body tilt and motion impact teleoperation?

2. Does spatial incompatibility between the tilt and motion directions of the operator's body and that of the robot further impact teleoperation?

3. Does the type of visualization interface reduce or compensate for the negative effects related to the operator's tilt and motion?

We propose to address these questions in this thesis by evaluating teleoperator performance and experience during simulated and real teleoperation in dynamic laboratory environments as well as in more ecological contexts. This investigation was structured around three experimental blocks. The first two blocks consist of fundamental experiments, each comprising two laboratory experiments under controlled conditions.

The **first block** (Exp I.a and Exp I.b) investigates whether spatial (in)compatibility effects manifest when the operator experiences bodily movements or inclinations during teleoperation. To explore this, experiments were conducted to evaluate teleoperation when their body motion and tilt directions were either spatially compatible or incompatible with the robot's orientation and motion directions.

The **second block** (Exp II.a and Exp II.b), building on the results of the first, seeks to address all three research questions. In this block, experiments were conducted to evaluate teleoperation when operator body movements are either spatially compatible or incompatible with the robot's direction, compared to static conditions. Additionally, different robot visualization interfaces were tested to determine whether a particular interface might be better suited for dynamic teleoperation scenarios.

The **third and final block** aimed to evaluate whether the effects observed in the laboratory could be transferred to more ecological settings. In this applied block, the operators were studied in more realistic conditions, focusing on their behavior during analog space missions (Exp III), in altered gravity environments (Exp IV), and when teleoperating with a real drone to perform an inspection task (Exp V).

11.3 | Teleoperation task simulation

Our main objective was to design an experimental protocol capable of simulating teleoperation tasks and reproducing a dynamic environment in the laboratory (blocks 1 and 2).

Equipment

To simulate teleoperation tasks, we used immersive virtual reality (Section 4.6 for a definition of virtual reality). Designing a real teleoperation task presents significant constraints. It requires robotics equipment, a space dedicated to the robot's task, and each session requires substantial preparation time. Moreover, there is a real risk of damaging the robot in case of errors. Virtual reality allowed us to simulate teleoperation tasks with a virtual robot in a virtual environment, thus eliminating the risk of damage and the need for a physical space for teleoperation. It gave us the freedom to choose the type of teleoperation task and interface we wanted and to vary them according to our experimental needs, for example, by testing different robot visualization interfaces without requiring complex modifications to robotic systems. Additionally, virtual reality enabled us to obtain precise performance measurements for teleoperation (e.g., tilt errors, number of collisions, completion time for tasks, etc.), and access to controller data allowed for detailed behavioral measurements regarding continuous robot control during teleoperation. Regarding our research questions, the virtual reality headset mainly allowed us to isolate our operators in the virtual environment during their body tilts and movements, so they had no visual cues about their body position. This recreated the typical visuo-vestibular conflicts found in teleoperation situations from a moving vehicle.

The virtual reality system used was the HTC Vive headset (right image of Figure 37). All of our tasks were coded in *C#* on Unity. The virtual robot could be controlled via the Logitech Gamepad F310 or the Logitech Extreme 3D Pro joystick (center and left image of Figure 37), depending on the experiments.



Figure 37: The HTC Vive virtual reality headset (right), the Extreme 30 Pro Logitech joystick (center), and the Logitech gamepad F310 (left).

Teleoperation task and choice of scenarios

Teleoperation tasks Teleoperation tasks vary significantly, ranging from simple monitoring to direct control for navigation or manipulation tasks, with different types of robots and different levels of autonomy (Section 1). The tasks reproduced for our experiments are those we believe are most affected by dynamic environments. As literature reviews show, gravito-inertial changes tend to have adverse effects, particularly on the perception

of 3D objects, distances, orientation, and self-motion (Section8). Consequently, we chose teleoperation tasks that require these specific abilities. The first task involved controlling and perceiving the orientation of a part of a static robot (Exp I). The second task involved perceiving and controlling the orientation of obstacles in a virtual environment, as well as controlling the orientation of a moving robot (Exp II, III, IV). The final task of real teleoperation consisted of inspecting a model of a space module, which required a good perception of the model in three dimensions and an accurate sense of distance to it (Exp V).

Teleoperation scenarios Furthermore, on board a moving vehicle, teleoperation scenarios can vary significantly. Various types of interfaces can be used, and the operator's position in the vehicle can influence peripheral vision, potentially causing partial or temporary visuo-vestibular conflicts.

In most of our experiments (Exp I, Exp II, and Exp V), we chose to recreate situations of complete visuo-vestibular conflict during teleoperation. To achieve this conflict, the VR or remote environment was displayed in an egocentric manner relative to the operator's head, meaning that the environments were always aligned with the operator's head regardless of body movements. In this way, participants had no visual cues about their own body's movements or position, as can happen in a moving control base that offers no visibility of the outside world.

In the experiments Exp I and Exp V, the operator's entire field of vision was dedicated to the robot's visual feedback, fully immersing the user in the robot's working environment. However, in Exp II, participants were immersed in a virtual environment with no directional cues. A screen in front of them displayed the robot's camera feed. The virtual environment was still aligned egocentrically, however, only part of the visual field was used to view the robot's feedback. This change was made because Exp II required the control of the robot's motion and displacement in its environment, inducing topic flow patterns in the camera feed. During protocol tests, when the entire visual field was dedicated to the robot's camera feed, the symptoms of motion sickness were too severe. Although this outcome is significant for teleoperation via HMD of a moving robot, for ethical reasons, we chose to modify the interface (switching from an HMD teleoperation scenario to a screen-based one) to reduce motion sickness and avoid discomfort for our participants.

The third block of experiments, however, was different in that Exp III and Exp IV induced a partial visuo-vestibular conflict. One of these experiments, aimed at recreating a teleoperation scenario from an airplane, involved teleoperating using a tablet positioned above the cockpit. Another, conducted during analogous missions, was performed on a computer screen while the participant was in a supine position. In both experiments, only part of the visual field was used to view the distant world (on screens), while participants retained peripheral vision of their physical environment, resulting in a partial visuo-vestibular conflict.

Measures The evaluation of teleoperation was carried out through the recording of both objective and subjective measures, inspired by the literature presented in Section 3. The objective measures were divided into two categories: behavioral measures and performance measures. While we acknowledge that performance measures could be considered a subset of behavioral measures, for the sake of clarity and readability, we chose to separate them. Therefore, our *performance measures* reflected indicators related to the teleoperation task objectives presented to the participants and were, therefore, highly task-specific. For perception tasks or orientation control of the teleoperated unit, we measured the degree of error between the target or perceived angle and the achieved angle. For the inspection teleoperation task, the performance measure recorded was the number of detected impacts compared to the actual number of impacts. *Behavioral measures*, on the other hand, included all metrics related to movement kinematics, such as movement timing, average speed, reaction time, task completion time, and time to reach a certain percentage of the target angle. These measures allowed us to identify whether certain visuomotor strategies or adaptations were implemented in dynamic environments, thereby aiding in the interpretation of the results. Finally, the *subjective measures* used referred to the operator's experience. We included items measuring operator workload, such as perceived mental or physical demands (items from the NASA TLX, Hart and Staveland (1988a)), as well as post-choice confidence and the level of symptoms experienced, such as motion sickness or cybersickness (Fast Motion Sickness scale (FMS), Keshavarz and Hecht (2011))).

11.4 | Dynamic environment simulation

Motion platform

To simulate a dynamic environment in the laboratory and investigate the effects of spatial compatibility, the VRtigo 6-axis motion platform PS-6TM-150 (Motion Systems, Poland) at the Neuroergonomic Centre at ISAE-SUPAERO was used (Figure 38). This platform allows for inclinations of up to 24° along three axes of rotation, as well as translational movements along all three axes. The platform was equipped with a seat as well as a joystick designed for flight simulation that was not used in these experiments. The platform's movements can be integrated and controlled via SDK within virtual reality environments created in Unity. This enables the automation of operator movements in VR experiments, facilitating the design of protocols where the directions of the platform's movements and those of the robot can be either compatible or incompatible.

Therefore, the combined use of the motion platform and immersive virtual reality allowed us to simulate various teleoperation scenarios (with different interfaces and tasks) in controlled dynamic environments, induced by the platform's movements. This enabled the reproduction of visuo-vestibular conflicts between the distant environment and the operator's environment, which are typical of teleoperation conditions in dynamic settings, such

as a moving vehicle. Additionally, this level of control allowed us to create spatial compatibility situations between the movements of the robot and those of the operator, helping us to better understand the impact of dynamic environments on the usability of teleoperation systems.

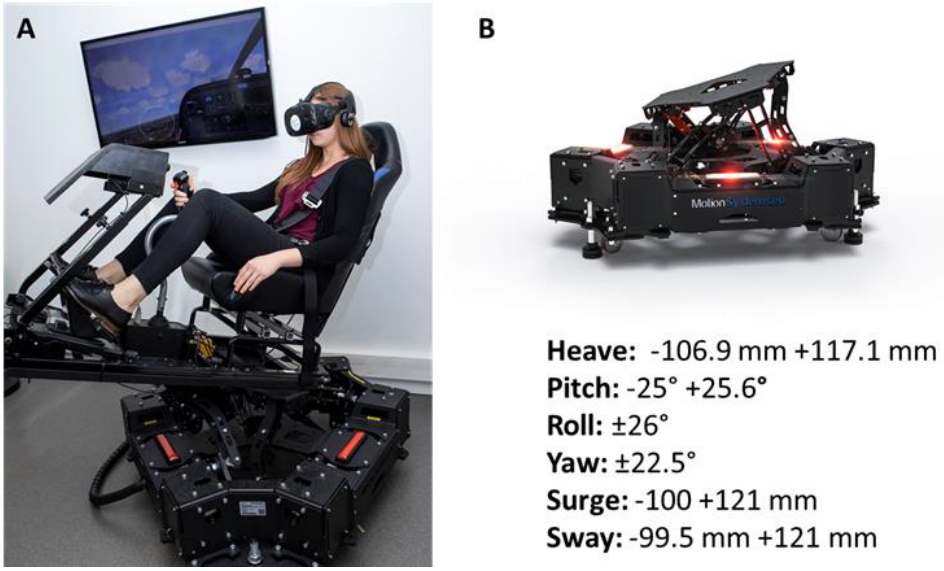

Figure 38: The VRtigo 6-axis movement platform

Supine body position

The use of the motion platform is optimal, but it cannot be easily displaced outside the laboratory. Sometimes, it is necessary to conduct tasks outside the Neuroergonomics Centre, as was the case for the experiments conducted as part of analog space missions (Exp III), as well as in the ISAE-SUPAERO aviary (Exp V). In these situations, we could not put the participants' bodies in motion. However, a simple way to reproduce a sensory conflict similar to that experienced in a dynamic environment is to tilt the operator's body by placing them in a supine position while isolating them visually using an HMD. Although this position does not create a strong conflict regarding body motion perception, as might occur when the entire body of the operator is moving, it places the operator in a modified gravitational force situation, requiring adaptation to this unusual force field (see for instance Le Seac'h and McIntyre (2007)). It also induces a visuo-vestibular conflict in the estimation of vertical orientation between the real world (perceived by the vestibular and somatosensory systems) and the distant world displayed in the HMD, potentially affecting the perceptual upright of a visual scene in the HMD, as in Dyde et al. (2006). This is why we chose this bodily position for Exp III and V, conducted outside the Neuroergonomics Centre.

11.5 | From lab to real-life settings, the importance of ecological validity

Understanding ecological validity

Research in neuroscience aims to generate models and theories to explain how the human brain functions within its environment. To achieve this, researchers adopt experimental approaches with a high level of control over experimental variables. They manipulate one variable while keeping others constant (Bucci-Mansilla et al., 2021). However, laboratory studies have limitations: *"The general concern is that due to the 'artificiality' and 'simplicity' of the laboratory, some (if not many) laboratory experiments do not adequately represent the 'nature' and 'complexity' of psychological phenomena in everyday life"* (Holleman et al., 2020). In this context, ecological validity, a concept closely related to external validity, aims to extend the generalization of results beyond laboratory conditions. While external validity seeks to generalize study results to different situations, populations, and conditions, ecological validity emphasizes generalization to real-world contexts. In their review, Holleman et al. (2020) discuss the origins of ecological validity. They explain that the concept was introduced by Brunswik (1947), whose goal was to create 'representative' psychological experiments to achieve the generalizability of laboratory results. According to Brunswik, researchers needed not only a representative sample of participants from the target population but also stimuli, tasks, and situations that are representative of a "target ecology".

Ensuring ecological validity

To achieve ecological validity, the experiment must reflect the natural and real conditions under which the phenomenon was observed. According to Schmuckler (2001), researchers can improve the ecological validity of their study along three dimensions: the nature of the research setting, where the environment should be representative of real-world conditions; the nature of the stimuli, where the stimuli used should be similar to those in the real world; and the nature of the responses, where the response required during the experiment should reflect natural behaviors representative of real situations and be relevant to the psychological process being studied.

More recently, in a review on ecological validity in cognitive ergonomics (Hoc, 2001), five key aspects were identified that a cognitive ergonomics study must adhere to achieve ecological validity.

1. An appropriate level of abstraction: The study should have a suitable level of abstraction, meaning that researchers should choose the right level of detail for the task so that it is neither too specific (risk of being non-generalizable) nor too general (risk of not being applicable to concrete situations).

2. Analysis of the work domain: Researchers should analyze the work domain where the tasks take place (knowledge of tasks, procedures, constraints) to create a study

that better reflects reality, so that operators are in a context close to the real one, and their cognitive processes are as well.

3. Reproduction of skills and expertise: Researchers should analyze and reproduce experimental tasks that require the skills and expertise of operators in the studied domain.

4. Perception-action loop: Tasks should replicate the perception-action loop present in the operators' real-world context.

5. Non-invasive methods: Research methods used should be as non-invasive as possible to avoid interfering with the operator's task and to ensure that the task is as representative of real-world conditions as possible.

In essence, highly controlled experimental studies ensure scientific rigor; however, this rigor can lead to experimental conditions that are quite far from the more complex and richer reality. Results obtained under such conditions may not be generalizable to real-world contexts. Conversely, studies that are close to real-world conditions to enhance ecological validity may be conducted in overly specific contexts, making results difficult to replicate in other situations or contexts. When introducing ecological validity, Brunswik supports that a more systematic approach to conducting ecologically valid experiments would first involve specifying the conditions to which researchers wish to generalize their results, then explaining how they plan to achieve it (Brunswik, 1947; Holleman et al., 2020).

Validating our experimental findings in real-life seetings

Therefore, good research must be both scientifically rigorous and ecologically valid to ensure its results can be reliably applied to real-world contexts. To achieve ecological validity, the experiment must reflect the natural and real conditions under which the phenomenon was observed. The first two blocks of our work involve laboratory experiments aimed at investigating the effects of highly controlled body movements of the operator on its teleoperation performance and experience. While virtual reality allowed for a certain level of ecological validity regarding teleoperation tasks and interfaces, these experiments remained highly controlled, making them quite experimental. As a result, they were relatively far from the reality of teleoperators' work, particularly concerning dynamic contexts and constraints related to the nature of teleoperation tasks; for instance, participants were aware of the artificiality of the task and did not experience the risk of damaging the robot.

Therefore, the third block aimed to evaluate whether the effects observed in the laboratory could be transferred to more ecological contexts. To this end, the experimental protocol of Exp II.b was adapted to two types of environments that are more representative of the real-world work of teleoperators.

Analog Mission This adaptation was used to conduct longitudinal studies during analog space missions, which are more representative of teleoperation conditions in extreme, isolated, and confined environments over long periods. A version was conducted by the crew members of the Mars Desert Research Station (MDRS) for 4 weeks (organized by ISAE-SUPAERO, see Figure 39). The operators' bodies were not in motion, but they were exposed to an unusual force field, and a partial visuo-vestibular conflict was induced by having crew members perform the teleoperation task while lying supine.



Figure 39: Crew 293 of the analog mission to the Mars Desert Research Station, Utah, 2024

Aircraft The same protocol from Exp II.b was also adapted to be conducted on board a moving aircraft, the ISAE-SUPAERO's Robin DR400 located at the Lasbordes aerodrome (Figure 40). The objective of this experiment was to reproduce different load factors induced by the inclination and movement of the aircraft.



Figure 40: ISAE-SUPAERO's Robin DR400 aircraft, located at the Lasbordes aerodrome

Real drone teleoperation The two previously mentioned studies enhance the ecological validity in terms of the working environment. The final study goes further by improving the ecological validity of the teleoperation task itself. A new experimental protocol was developed and conducted in the ISAE-SUPAERO aviary, where participants controlled a real drone (DJI FPV Combo – First-Person View Drone, Figure 41) to perform an infrastructure inspection. This approach ensured that the teleoperation objective, stimuli, and participants' responses were more closely aligned with the real-world tasks and challenges faced by teleoperators.



Figure 41: DJI FPV Combo- First-Person View Drone

CONTRIBUTIONS

III. Effects of spatial (in)compatibility between robot and teleoperator tilts and motions

The first studies conducted as part of this work focus on the potential effect of spatial (in)compatibility between the operator's body orientations and those of the teleoperated unit on teleoperation performance. To our knowledge, no prior research has investigated these effects in the context of movement, nor have findings been applied to teleoperation tasks. To explore these questions, we conducted a preliminary study to assess whether the effects of spatial (in)compatibility extend to the perception and control of a remote robot in virtual reality. A first teleoperation task in virtual reality was designed, and a research protocol was developed to address the following two questions:

1. Does spatial incompatibility between the direction of the operator's body tilt and that of the robot impact the perception of the robot?

2. Does spatial incompatibility between the direction of the operator's body motion and the manual movement performed impact the control of the robot?

The results of this preliminary study aimed to explore the concept of spatial (in) compatibility in the field of teleoperation and to guide the directions of our future research. A pilot study was then conducted, leading to protocol adjustments, before carrying out a larger-scale study. The pilot study presented in this section was published in an article and then presented as a poster at the *International Astronautical Congress 2022*, and the main study is currently under (minor) revision for the journal *ACM Transactions on Human-Robot Interaction*.

12 | The pilot study

12.1 | Introduction

As discussed in Section 8, body tilts and movements can impact human sensorimotor performance. Perceptual alterations can affect orientation perception (vertical and horizontal), as well as the perception of object size, distance, motion, acceleration, and interception timing. Additionally, body tilt and altered force fields are known to affect manual control paradigms, such as pointing and manual tracking tasks. If these effects observed in the literature transfer to teleoperation tasks, we might infer that the perception and control of the remote robot could be impaired (Table 3). However, to date, it seems that no study has been conducted on the transfer of these effects to teleoperation.

Moreover, literature exploring the compatibility between stimuli and responses has noted that spatial incompatibilities can impact performance (Section 10). For instance, Simon's paradigms have shown that humans react less quickly and with a lower precision when the stimulus and distractor (presenting directional cues) are located in the opposite spatial location as the expected response. This phenomenon of spatial (in)compatibility occurs even when the distractor is irrelevant to the task and belongs to a different sensory modality, such as an auditory distractor in a visuomotor task. For example, participants respond slower to a light stimulus on the right side of the screen when it is accompanied by a sound in the left ear, compared to a sound in the right ear (Simon and Craft, 1970). On board a moving vehicle, a teleoperator might find themselves in situations where the vehicle's movements tilt the operator in a direction opposite to that of the robot they are controlling or monitoring. We, therefore, question whether these body tilts, providing directional cues based on the tilt direction, might induce effects similar to those of irrelevant auditory distractors observed in Simon and Craft (1970) and thus alter response times in a visuomotor task. If these spatial (in)compatibility effects also manifest in teleoperation tasks from a moving vehicle, this shift in reaction time could potentially influence the performance of perception and control of a remote robot in situations where the operator's body movements are incompatible with those of the robot.

Another important factor that may influence teleoperation performance is the operators' confidence and certainty in their choices. Although these terms are distinct —- certainty relating to the posterior distribution of latent variables relevant to the task, and confidence being related to commitment to a given choice (Pouget et al., 2016) —- their impact on teleoperation performance could be closely related. The relationship between confidence and reaction time is controversial, yet most studies indicate that, in perceptual decision tasks, reaction time is generally negatively correlated with certainty or confidence (Fossataro et al., 2020; Pouget et al., 2016). We believe this could affect teleoperation performance and the operator's situational awareness. Additionally, although increased variability in Subjective Visual Vertical has been reported when participants are tilted (Heereman et al.,

2015), to our knowledge, the literature has not explored the relationship between SVV results and subjects' confidence after making a choice.

To address these research questions, we designed and tested a preliminary version of an experimental protocol using virtual reality and a motion platform aiming at studying the effect of body tilt and movement on the performance and confidence of orientation perception and control of a virtual robot, and investigating the manifestation of spatial (in)compatibility effects in teleoperation from a dynamic environment. The VR task of this protocol first involved orienting the panels of a rover to a certain angle, then performing a subjective visual vertical (SVV) test, and finally estimating the orientation of the rover's panels. In each trial, participants were asked to indicate their confidence level in their responses. Participants could be upright, tilted in a spatially compatible manner, or tilted in an incompatible manner relative to the panels' orientation. The SVV task aimed to verify that the perception of verticality was affected, and the protocol design allowed us to separately analyze the effects of body tilt and movement on perception and manual control performance compared to controlled conditions.

We hypothesized that participants' body orientation would alter their SVV, as well as their perception (accuracy, reaction time) and control of the robot's orientations (accuracy, precision, and response time), along with their confidence. Additionally, as in Simon's paradigm, we assumed that the observed reductions would be more pronounced in spatially incompatible conditions than in spatially compatible conditions.

12.2 | Methods

Participants

17 healthy volunteers participated in the study (7 females; mean age = 25.75 ± 4.4), students of the French Aerospace Engineering School ISAE-SUPAERO. Participants had normal or corrected-to-normal vision, no history of neurological or psychiatric diseases, and were free of the regular use of medication.

Ethics statement

All participants were informed of their rights and gave written informed consent for participation in the study, according to the Declaration of Helsinki. The research was carried out fulfilling ethical requirements by the standard procedures of the ISAE-SUPAERO.

Experimental device

Participants were placed on a motion platform (VRtigo 6-axis movement platform, PS-6TM-150, MotionSystems), in a dark environment, VR headset (HTC Vive Pro) on and the joystick (Logitech Extreme 3D Pro) on their lap. The tasks were designed in Unity3D/ *C#*.

Study design and procedure

The experiment was composed of 80 trials and lasted approximately 30 minutes. Each trial included several tasks (Figure 42). Before the main experiment, participants were familiarized with all parts of the task. Each trial began with the chair in a vertical position, meaning that at the end of every trial, the chair returned to its neutral/vertical position before the beginning of a new trial (Figure 42A).

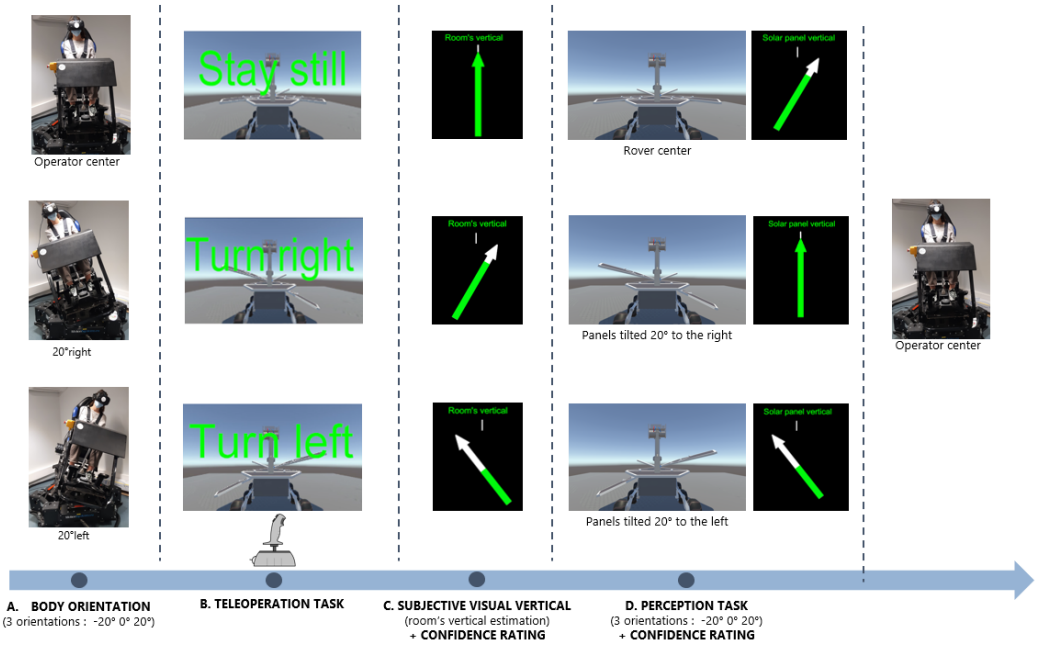

Figure 42: The time course of one trial with A) 3 possible body orientations, B) 3 possible instructions for the teleoperation task, C) subjective visual vertical and associated confidence rating, and D) perception task with the same orientation as the teleoperation task B and associated confidence rating. Then the motion platform moved to the neutral position.

The teleoperation task (Figure 42B) was designed to evaluate the effect of movement direction on manual control. Participants were tilted in one of the 3 possible orientations (0°; 20° to the right and left), rotated in the roll axis. During chair roll movement, subjects had to teleoperate rover panels using the joystick. They were asked to either (1) center the rover's solar panels in a horizontal position ("Stay still"), (2) turn the panel to the left to align them with a reference rod oriented at 20° to the right and hold the position ("Turn Left") or (3) turn the panel to the right to align them with a reference rod oriented at 20° to the left and hold the position ("Turn Right").

The Subjective Visual Vertical (SVV) test (Figure 42C) was designed to evaluate the effect of body orientation on subjects' subjective visual vertical. Participants had to orient

an arrow in the direction of the room's vertical, felt through their vestibular and proprioceptive sensations. After each response, subjects indicated the level of confidence in their response by moving (up and down via thumb movements on the joystick button) a green cursor on the arrow. The greener the arrow, the more confident the subject was.

The perception task (Figure 42D) was designed to evaluate the effect of body orientation on the perception of the orientation of the teleoperated object. The position of the rover's solar panels was shown for 2 seconds. The screen was then cleared. Subjects were asked to align an arrow with the rover panels' vertical while being in one of the three possible body orientations. Then, as previously, subjects indicated their level of confidence. The vertical is defined within the earth frame of reference and aligns to the gravity direction, i.e the perpendicular of the horizon. Here, what we call the "vertical of the solar panels" corresponds to the perpendicular of the solar panels. We chose the term vertical inspired by the Subjective Visual Vertical task. Muller (1916) and Aubert (1861) showed that body orientation impacts vertical perception. In this experiment, we evaluate if an operator's body orientation impacts their perception of an axis' vertical (thus, the rover panels perpendicular) as well.

Statistical analysis

In this pilot study, only the **perception tasks** and the **Subjective Visual Vertical test** were analyzed, which allowed us to submit the article on time for the *International Astronautical Congress* 2022. However, we were unable to devote sufficient time to analyzing the **teleoperation task** that focused on the effect of movement direction on manual control. This analysis, therefore, investigated the relationship between body tilt, the orientation of the teleoperated object, perceptions of vertical orientation, and post-choice confidence within the teleoperation task. We examined response accuracy (i.e., angle error in indicated panel orientation), Response Time (RT), and the level of confidence participants had in their visual perception for the Subjective Visual Vertical and Perception tasks.

All 17 subjects were included in the analysis. Data were analyzed by a 2-way repeated measures ANOVA with Operator's orientation (Op left, Op right, and Op center) and Panels' orientation (Rov left, Rov right, and Rov center) as factors. If Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($p < .05$), degrees of freedom were corrected using Greenhouse-Geisser sphericity corrections. All post hoc analyses were performed with a Bonferroni correction. All statistical analyses were performed using the JASP 0.18.3 software. The evaluation of the influence of body orientation lateralization (right/left) on participants' performance in the SVV and perception tasks, as well as the lateralization of panel orientation in the perception task, was exploratory, as no specific hypotheses were made for these factors.

12.3 | Results

Influence of body tilt in the Subjective Visual Vertical test (SVV)

Results revealed a significant main effect of Operator's orientation in SVV tests regarding confidence ($F_{2,30} = 13.70$, p = .002, $\eta_p^2 = .48$) and response times ($F_{2,30} = 18.23$, $p < .001$, $\eta_p^2 = .55$). Post hoc comparisons showed the operators tilted to the left or to the right were less confident (p < .001 and p = .002 respectively) (Figure 43, on the left) and had longer response times (p < .001 and p = .01 respectively) (Figure 43, on the right).

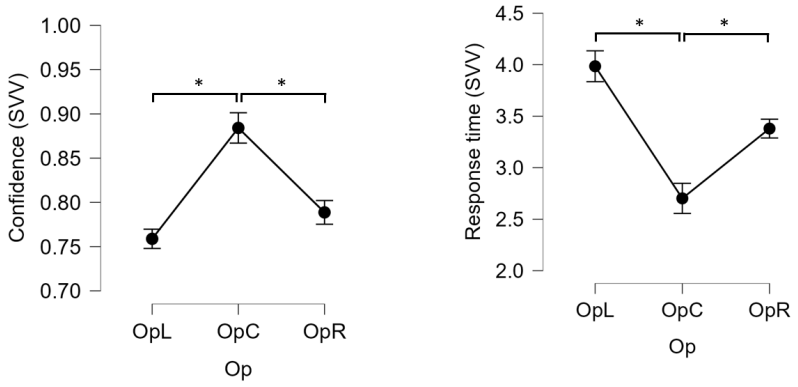

Figure 43: Effect of body tilt on confidence (on the left) and response times (on the right) during SVV task. Asterisks indicate significance (p<0.05).

Note that because of the experimental protocol, the subjects estimated their subjective visual vertical position for different rover panels' orientations. As expected, there were no main effects and no interaction for confidence ($F_{2,30} = 3.35$, p = .07, $\eta_p^2 = .18$ and $F_{4,60} = 1.79$, p = .18, $\eta_p^2 = .11$, respectively) nor response times ($F_{2,30} = 1.05$, p = .36, $\eta_p^2 = .07$ and $F_{4,60} = 0.43$, p = .71, $\eta_p^2 = .03$, respectively).

Influence of body tilt and panel orientation on confidence in the perception task

The two-way ANOVA revealed a significant main effect of Operator's orientation in the perception task regarding confidence ($F_{2,30} = 8.62$, p = .002, $\eta_p^2 = .37$). Post hoc analyses indicated decreased confidence during left and right tilts compared to the central position (p = .003 and p = .004 respectively).

The analysis also revealed a significant main effect of the Panels' orientation ($F_{2,30} = 5.40$, p = .019, $\eta_p^2 = .27$) on operators' confidence in their perception. Post hoc comparison indicated lower confidence when the rover's panels were tilted to the left compared to the centered position (p = .012).

Furthermore, we found a significant interaction of Operators' orientation × Panels' orientation ($F_{4,60} = 4.27$, p = .02, $\eta_p^2 = .22$). Post hoc analyses revealed that the effect of the

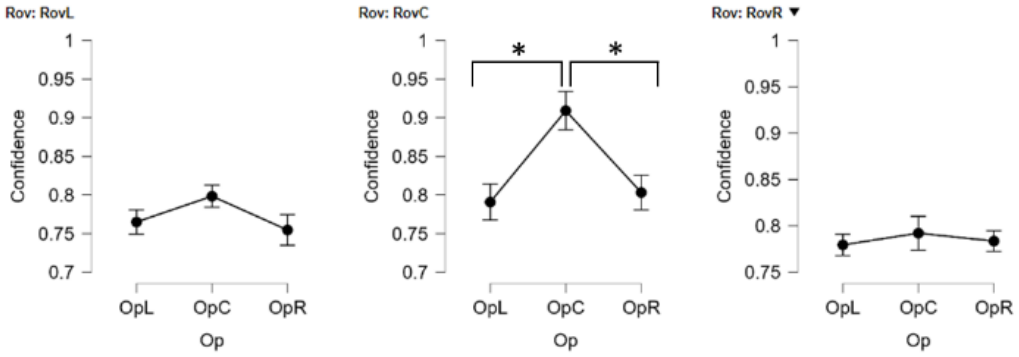

Figure 44: Interaction of body tilt and panels' orientation on confidence levels during the perception task. Asterisks indicate significance (p<0.05).

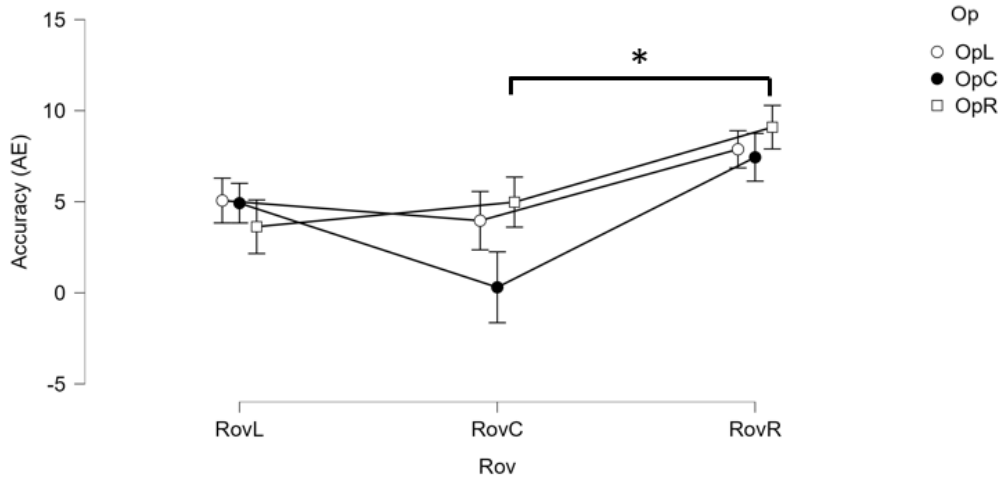

Figure 45: Effect of panel's orientation on accuracy in degrees of angle error (AE) in the perception task. Asterisks indicate significance (p<0.05)

operator's orientation was present only for the panel's central orientation (decreased confidence during left and right tilts with p < .001 for both tilts compared to the central position) but not when panels were inclined.

Influence of panels' orientation on accuracy in the perception task

A significant main effect of Panels' orientation was found regarding subjects' response accuracy ($F_{2,14} = 5.15$, $p = .022$). Post hoc analyses revealed a significant difference in responses' accuracy between Right and Center positions of the rover's panels, participants made larger angle error when the rover's panels were tilted to the right (p = .012). Furthermore, a significant interaction of Operators' orientation x Panels' orientation ($F_{2,14} = 3.89$, $p = .02$) was found, indicating that the difference in accuracy is higher between the condi-

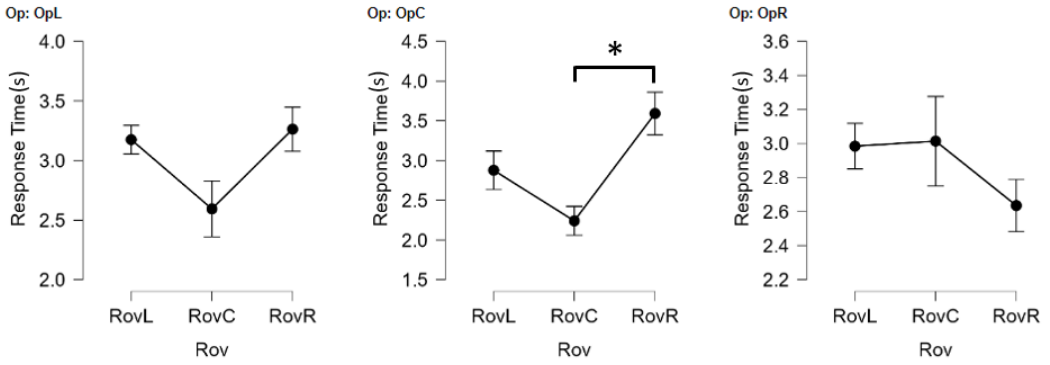

Figure 46: Interaction of body tilt and panels' orientation on Response Time (s) during the perception task. Asterisks indicate significance (p<0.05).

tion in which both the operator and the rover are centered and all the ones in which the rover's panels are tilted to the right.

Influence of Panels' orientation on response time in the perception task

A significant main effect of Panels' orientation was found regarding subjects' response time ($F_{2,30} = 6.89$, $p = .009$, $\eta_p^2 = .32$). Post hoc analyses revealed that participants took more time to respond when the panels were tilted to the left or the right (p = .043 and p = .003 respectively). No significant main effect of operator's orientation was found ($F_{2,30} = 0.28$, $p = .63$, $\eta_p^2 = .02$). There was a significant interaction of Operators' orientation × Panels' orientation ($F_{4,60} = 4.92$, $p = .005$, $\eta_p^2 = .25$) indicating that the effect of longer response times for a tilted panel was present only when the operator was centered and the panels were tilted to the right (p < .001) (Figure 46).

12.4 | Discussion

In this study, we set up a new virtual task to investigate how body tilt and motion impact teleoperation performance and confidence. We focused on evaluating the impact of body orientation on the operator's perception of the teleoperated robot and its subjective visual vertical (SVV). Our results show that both body tilt's orientation and the teleoperated object's orientation impact the confidence operators have in their response regarding their perception of the object in VR. Body tilt also impacted response time, as well as the confidence participants had in their responses in the Subjective Visual Vertical test. Thus, body tilt impacted confidence for both visual and somatosensorial/vestibular perceptions.

SVV results In the SVV test, the fact that participants had longer response times was associated with lower confidence in their perceptual choices, which is consistent with previous work (Kiani et al., 2014). Also, we obtained, as expected, a decreased confidence

in tilted positions for both participants' subjective vertical (SVV) and object orientation estimations (perception task). Thus, being tilted influences participants' perceptual confidence in their vestibular, somatosensorial, and visual cues. However, body orientation and spatial compatibility with the remotely controlled object orientation did not affect the participant's orientation estimation either in terms of accuracy nor response time.

Spatial compatibility We expected that spatially incompatible combinations of operators' body tilt and rovers' orientation would induce larger response times and lower confidence levels than the compatible ones. However, the results didn't reveal any particular trend regarding the spatial compatibility effect. Further research is needed to address these phenomena by taking into account the limits of the current experiment (see below).

Effect of body tilt on perceptual confidence Why does body tilt decrease confidence in perceptual tasks? Post-choice confidence represents the probability that the perceptual decision made is correct based on available sensory evidence. For instance, in our perception task, confidence would represent the probability that the chosen orientation was the right one based on the visual cues perceived by the participant. In other words, Mamassian defined visual confidence as "*the ability of the observer to make a good inference on the validity of the response corresponding to this perceptual decision*" (Mamassian, 2016). In their study, Drugowitsch et al. found that "*bounded evidence accumulation explains decision accuracy, speed, and certainty*" (Drugowitsch et al., 2014). This means that the vestibular and somatosensorial afferences (evidence) perceived by our tilted participants could have been perceived as unbounded "unusual" and conflicting sensory evidence and thus challenged visual evidence, leading to lower confidence rating (in both tasks) and higher response time (in SVV only). Likewise, Bernard-Espina et al. showed the importance of gravity signals in sensory-motor tasks (Bałaj et al., 2019). They proposed that "*the neural networks in the parietal cortex involved in the cross-modal processing of sensory information are more efficient when the otolithic afferences correspond to an upright head position*". They explain that humans are not used to performing sensory-motor tasks tilted with respect to the vertical. Thus, they hypothesize that gravity affects performance because of this "usualness effect"; "*the synaptic weights necessary to perform visuo-proprioceptive transformations are learned through experience. Since the upright position is largely the most common head orientation in our everyday life, it is possible that these neural networks become "optimized" for such head position and significantly less effective when otolithic afferences signal a head tilt for which we have a limited experience*". Besides, studies showed that performance, confidence, and reaction time were linked (Bernard-Espina et al., 2022; Fossataro et al., 2020) , one would then expect to observe a decreased confidence during head and body tilt.

Why does body tilt affect participants' confidence but not the accuracy of orientation estimation? Although confidence levels tend to be well-correlated with accuracy, recent

experiments report that confidence and accuracy can be dissociated: "*If confidence is available and well-calibrated, low confidence is an important signal to allocate more resources to a task and hopefully improve task performance through perceptual learning*" (Mamassian, 2016). Also, the Accumulation Of Evidence Model proposes that confidence depends on the quantity and quality of sensory evidence accumulated at the decision time. It assumes that, in uncertainty, waiting longer to process new evidence helps the observers reach a better decision. Thus, low confidence does not always correlate with low accuracy. This could explain why our participants showed decreased confidence and RT but no decrease in accuracy for the Perception task. Being tilted may have decreased their perceptual confidence, indicating that they needed more time to accumulate evidence to better estimate the orientation of the rover's panels. In teleoperation, low visual confidence could be an important reminder to slow down and take a step back to check other instruments' settings to verify that one's not disoriented in space, for instance.

Limitations and prospects for improvement Several limitations of the study must be acknowledged. A first limitation is that our study group was quite limited (n=17), and thus was not reflective of the general population, mostly because most subjects were students aged between 23 and 34.

Then, accuracy (AngleError) and RT values revealed 2 major limits of the experimental protocol tested here. First of all, regardless of the operator's position, as soon as the rover's panels had to be reported as being oriented to the right, accuracy errors increased significantly. This reveals a problem with the grip of the joystick. Indeed, subjects reported having more difficulties performing the supination hand movement to orient the joystick (and thus the arrow) to the right than to the left. In other words, pulling the joystick to the right was more difficult than pushing it to the left. **For future experiments, the use of a gamepad would be more appropriate in the final version of the experiment. The manual control will be done by thumb movements which will facilitate teleoperation and eliminate this experimental bias.** Second, in the condition where the operator is seated upright and the panels are horizontal, RT and Angle error values of the perception task were particularly low (even equal to zero for Angle Error). In this condition, the upright participant saw the rover, which had horizontal panels. He/she had to make sure that the arrow presented was perpendicular to the panels displayed for 2 sec before. However, here the initial position of the arrow to be oriented was, by default, positioned perpendicular to the rover's panels when these were placed horizontally. Thus, the subject had nothing to perform, he/she just had to validate the answer. In the other conditions, he/she had to orient the arrow and validate his/her answer. The measurements of RT and angle error of this OperatorCentered/RoverCentered condition were thus hardly comparable with other conditions. **To remedy this, the arrow must be randomly positioned between trials so that participants always have to orient the arrow in the estimated panels' orientation.**

Furthermore, whether it was for the orientation of the arrow indicating earth or panels'

vertical, the arrows to be oriented were framed by a title and a marker, and were always oriented aligned with the participant's head axis. Meanwhile, in actual SVV tests, the rods that participants have to orient are randomly oriented, and no text is displayed. This, with our small sample group, could explain why we didn't observe the expected E-effect (tilt overestimation) in the SVV test. Also, participants had to perform the SVV test and the panels' orientation estimation test one after the other. The mental switch between estimating the room's vertical and the rover's panel perpendicular was difficult for some participants. We were no longer measuring the perception of estimation but also participants' ability to switch between two frames of reference. Which is interesting but not what we wanted to evaluate here. **Thus, to remedy these problems, we propose to remove the SVV test from the rover task (Teleoperation and Perception) and make it an independent test that participants perform before the rover task.**

HIGHLIGHTS

1. In conclusion, this pilot study has already shown that, in orientation estimation tasks, body tilt influences participants' confidence level (visual perception of the teleoperated unit and SVV) as well as their response time (SVV only).
2. Despite certain limitations, this paradigm is innovative and promising, highlighting interesting trends.
3. These limitations are carefully addressed in the next large-scale experiment, thereby strengthening the validity and applicability of our findings.

13 | The main study

13.1 | Introduction

The prospects for improvement mentioned in the discussion of our pilot study have been considered and applied to this study. (1) In this updated version, the SVV was separated from the teleoperation and perception tasks to minimize confusion between vertical estimation and the perception of the perpendicular of the rover's panels. (2) To improve clarity and understanding of the protocol, the task previously called the "Teleoperation Task" is now named the "Manual Control Task," as the term "teleoperation" could refer to both the perception task and the control of the rover. (3) In the pilot study, participants experienced more difficulty pushing the joystick than pulling it, regardless of the movement conditions. Consequently, the joystick has been replaced with a gamepad, allowing manual control to be performed with thumb movements. This change aims to facilitate teleoperation and reduce the biases observed in the previous experiment. (4) The Subjective Visual Vertical was revised so that the rods participants had to orient were randomly positioned, and no text was displayed. (5) Moreover, we decided to change the instructions for the manual control task to reduce spatial confusion. In the rover panel control task (referred to as the "teleoperation task" in the pilot study), participants were originally instructed to "turn right" or "turn left" to align the panels with a rod located either to the right or left. However, these instructions could be spatially confusing. For example, when participants saw the instruction "turn right," the panel would move to the right, but it was meant to align with a rod located on the left side of the rover's central axis. To address this issue, the robot control instructions were modified to limit the spatial ambiguity caused by the previous "turn right" and "turn left" commands. In this updated version, participants were instructed to align the panels with rods labeled A, B, and C. This way, the instructions no longer carried potentially conflicting spatial characteristics regarding the side of the rod the participants needed to align with. (6) In the perception task, we ensured that the arrow used to indicate the perpendicular of the panels was randomly positioned between trials. Hence, participants always had to orient the arrow according to the estimated orientation of the panels, even when they were horizontal (which was not the case in our pilot study). (7) Additionally, for clarity, we also modified the instructions for the perception task. We asked participants to align the arrow with the perpendicular of the rover's solar panels, rather than the "vertical of the rover's panels," a term used in the pilot study that turned out to be inappropriate for this task and could lead to confusion, especially right after completing the SVV task.

As a reminder, the objective of this study was to investigate how spatial (in)compatibilities between the directions of participants' body roll tilts and motion, and that of the teleoperated unit, could affect manual control, perception, and confidence during teleoperation in virtual reality. To this end, we designed and, here, updated a simple visuomotor task in

virtual reality that participants had to perform while seated on a motion platform. The task consisted of the remote control and the orientation estimation of a rover's panels (presented as ego-centered). Participants' body tilt and movement could be spatially compatible or incompatible with the direction of the panels' orientation. At each trial, participants reported a level of confidence in their responses. Before performing this task, the Subjective Visual Vertical test was performed. This allowed (1) to verify that the experimental setup/chair tilt did induce an alteration of the perception of the vertical and (2) to make sure that our participants had no inner ear damage, which could bias the data.

As previously, two hypotheses were formulated regarding the impact of spatial incompatibilities on participants' performance:

1. Our first hypothesis is that such incompatibilities between the participant's whole body rotation and their manual movement directions would decrease their manual control accuracy, precision, and response times.

2. Our second hypothesis is that spatial incompatibilities between the participant's body tilt and the teleoperated object's orientation would decline participants' accuracy and response time in estimating the object's orientation, as well as decrease their post-choice confidence.

13.2 | Methods

Participants

A total of 54 healthy volunteers, students, and staff of the French Aerospace Engineering School ISAE-SUPAERO participated in the study (12 females, 4 left-handed, mean age = 27.5, SD = 9.6). Participants had normal or corrected-to-normal vision, no history of neurological, psychiatric diseases, or severe motion sickness, and were free of the regular use of medication.

Ethics statement

All volunteers were informed of their rights and gave written informed consent for participation in the study, according to the Declaration of Helsinki. This work was approved by the Comité d'Éthique de la Recherche - CER at Université de Toulouse (CER number 2022-482).

Experimental device

The study was conducted in the VR research room within the French Aerospace Engineering School ISAE-SUPAERO. Participants were placed on a motion platform (VRtigo 6-axis movement platform, PS-6TM-150, MotionSystems), in a dark environment (no visual cue

indicating their body orientation), with a VR headset (HTC Vive Pro) and a gamepad (Logitech gamepad F310) (Figure 47).

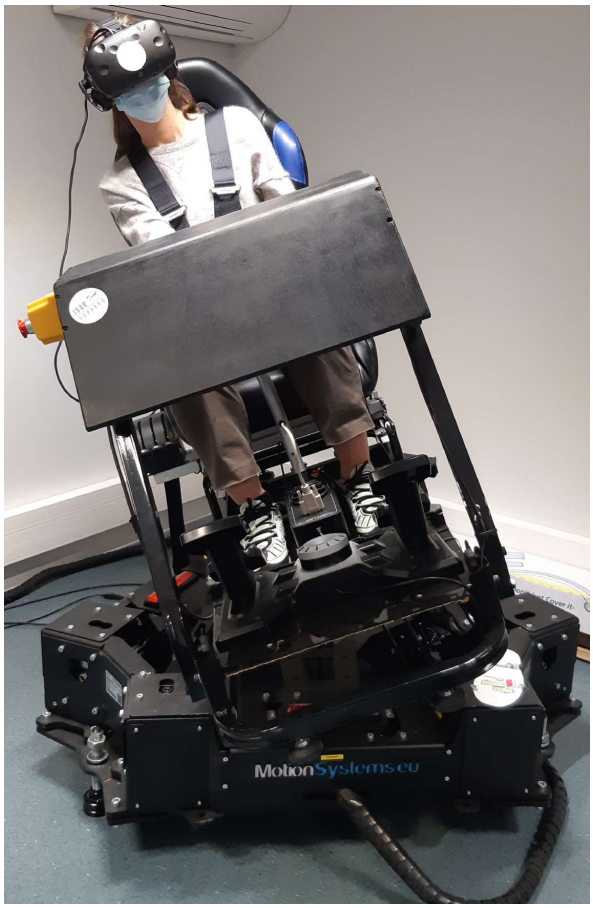

Figure 47: Experimental setup including the VRtigo motion platform, the HTC Vive Pro VR headset, and the Logitech gamepad.

13.2.1 | Study design and procedure

The study involved 3 virtual reality tasks (developed in Unity3D/C#) that participants performed while a motion platform modulated their body orientation and movement. All visual presentations of tasks were egocentric; in other words, they were tilted with the body rotation.

First of all, participants performed a Subjective Visual Vertical test (SVV) (Figure 49) and then a manual-control and perception tasks (Figure 48). The Subjective Visual Vertical was composed of 10 training trials and 10 task trials, the manual-control and perception task of 20 training trials, and 60 task trials divided into 2 sessions of 30 trials each. During

the study, participants had several 5-minute breaks. The experiment consisted of a total of 100 trials (training and task) and lasted approximately 45 minutes.

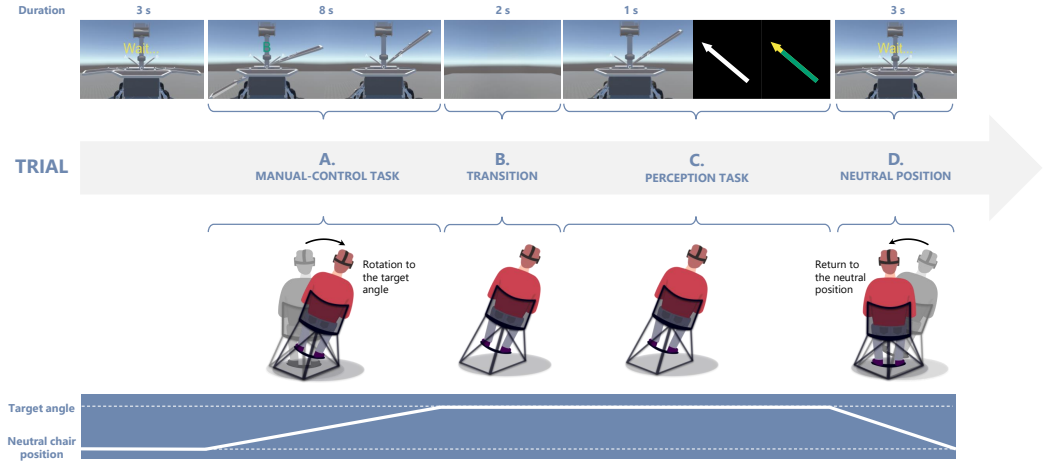

Figure 48: Manual-control and perception tasks. An example of the time course of a spatially incompatible trial with A) the manual-control task performed during the chair roll tilt movement to the target angle (here the participant had to align the panels with the "B" rod), B) 2 seconds of transition between the tasks, C) the perception task performed during the static tilt of the chair associated with confidence rating (the greener the arrow, the more confident the participants were), then D) the motion platform moved back to its upright neutral position.

Before the main experiment, participants were familiarized with all parts of the tasks. A short training sequence, including feedback, for all tasks along with instructions, was provided. Each trial began with a neutral chair position (Figure 48A).

The SVV test (Figure 49) was designed to evaluate the effect of body orientation on participants' subjective visual vertical. Participants were tilted in 5 possible orientations (0°; 12°; 24° to the right (12R, 24R) and left (12L, 24L), rotated in the roll axis. When oriented, participants had to align a human pictogram with the direction of the room's vertical felt through their vestibular and proprioceptive sensations. To help participants understand the concept of verticality, the authors asked them to orient the figure the way they thought a person would be if they were standing in the room in front of them. Participants were asked to use the right pad (right and left thumb movements) of the gamepad to rotate the figure and then to validate their answer by pressing the right trigger pad. After each response, the figure turned yellow, inviting the participants to indicate the level of confidence they had in their given response by moving (up and down thumb movements on the right pad) a green cursor. The greener the figure, the more confident the participants were. The manual-control and perception tasks (Figure 48) consisted of multiple trials of participant orientation in one of the five possible orientations, manual-control task while the participant's body is in movement, perception task in a body orientation (no movement) and then

confidence rating.

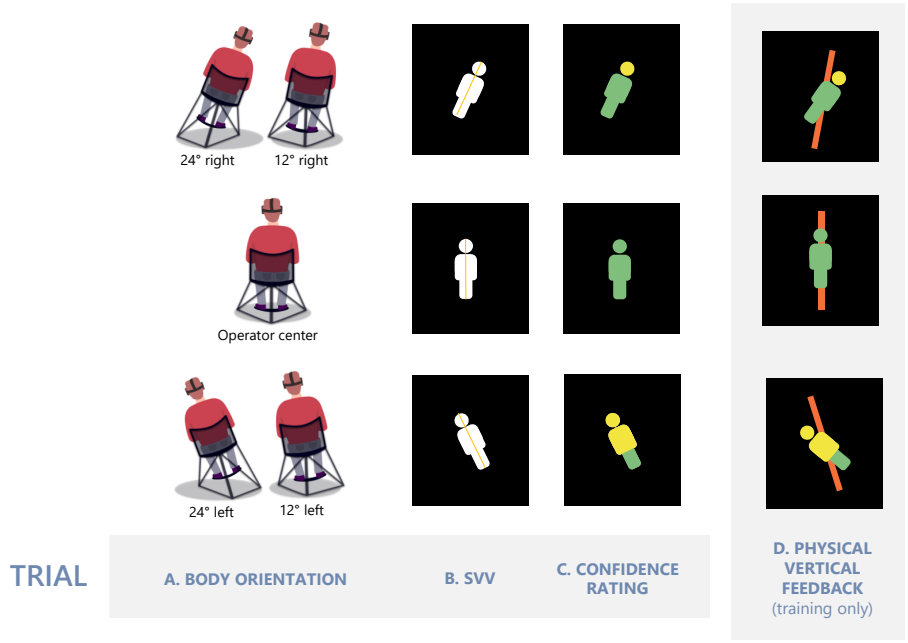

Figure 49: Subjective Visual Vertical test (SVV). The time course of one trial with A) 5 possible body orientations, B) the subjective visual vertical test associated with C) confidence rating (the greener the figure was, the more confident the participants were), and D) feedback on the orientation of the physical vertical represented by the orange line, for training trials only. Then, the motion platform moved back to its upright neutral position.

The manual-control task (Figure 48A) was designed to evaluate the effect of compatibility between the body movement and manual-control directions. Therefore, in this task, participants had to control the rover's panels tilt using the gamepad while their body was moved in 5 possible orientations (0°; 12°; 24° to the right and left), rotated in the roll axis. Before chair movement, an "A", "B", or "C" instruction was displayed. During chair movement, they were asked to either center the rover's panels in a horizontal position ("C") or align the panels with the rod tilted at 20° to the right ("A") or to the left ("B"), and then hold the position until the rover disappears (Figure 50).

The perception task (Figure 48C) was designed to evaluate the effect of compatibility between the body orientation and the teleoperated object orientation on the perception of the orientation of the teleoperated object. The expected position of the rover's panels in the manual-control task was shown here for 1 second. The screen was then cleared. Participants were asked to align an arrow with the solar panel's perpendicular (right and left thumb movements to rotate the arrow) while being in one of the five possible body orientations. Then, as in the SVV test, participants indicated their level of confidence.

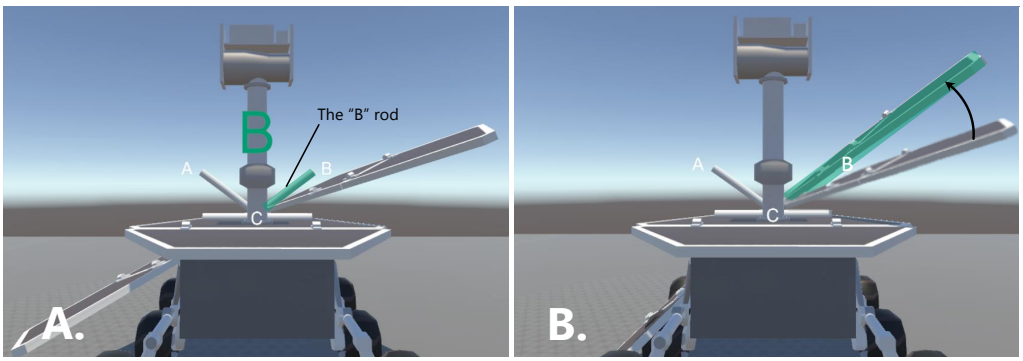

Figure 50: Manual-control task. An example of a trial in which the participant had to align panels with the B rod. A) The rover's panels are in an initial position, and the "B" instruction is displayed in front of the rover, prompting the participant to align the panel with the "B" rod (here illuminated in green). B) After the instruction vanished, the participant tilted the panel to the left to ensure its right side aligned with the "B" rod.

The manual-control and perception tasks could be performed in 3 experimental conditions: the control, spatially compatible and incompatible conditions (Figure 51). In the control conditions, participants performed the manual-control and perception tasks in an upright sitting position with no body movement or induced tilt. In spatially compatible conditions, the participant's whole body and manual movements were in the same direction (manual-control task) and the participant's body and the rover's panels' were tilted in the same direction (perception task). Whereas in spatially incompatible conditions, the body movement and tilt were in opposite directions to those of the manual control and panel orientation, respectively.

Data processing and statistical analysis

We investigate the effect of (in)compatibility of a participant's body and the teleoperated object orientations and movements on their perception and control of the teleoperated object orientation as well as post-choice confidence within a simple teleoperation task. We performed an SVV test to validate the operability (correct functioning) of our setup with respect to alterations in the participants' vertical perception. Thus, for orientation perception tasks of both the vertical and the teleoperated object (perception and SVV tasks), we examined response accuracy (i.e., angle error in indicated orientations) and response time as well as the confidence participants had in their visual perception. During rovers' panels' teleoperation (manual-control task) we examined response accuracy (i.e. the average position of the panel angle in the last 5 seconds of trials, with 1 as the target angle to be reached), precision (i.e, motor responses' standard deviation during manual control in the last 5 seconds of trials) and Response Time (start of manual movement and the time to reach 50% of their response angle). Two outlier subjects were excluded from the analysis

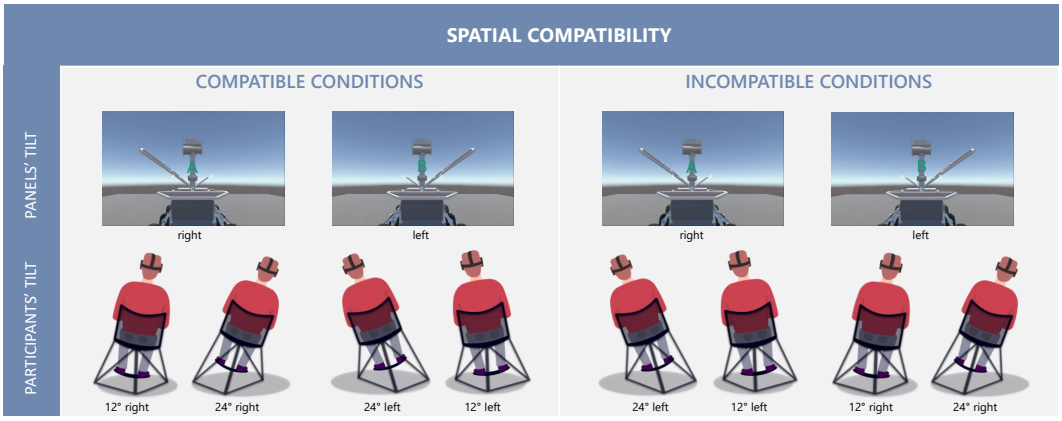

Figure 51: Spatial compatibility conditions. In spatially compatible conditions, the participant's whole body and manual movements were in the same direction (manual-control task), and the participant's body and the rover's panels' were tilted in the same direction (perception task). In spatially incompatible conditions, the body movement and tilt were in opposite directions to those of the manual control and panel orientation, respectively. The body tilts could reach target angles of 12 or 24 degrees to the right or left.

of the perception task.

Data preprocessing was performed using Python programming. SVV data were analyzed using a 1-way repeated measures ANOVA with participant orientation (L12, L24, R12, R24, and 0) as a grouping factor. Manual-control and Perception tasks data were analyzed using a 1-way repeated measures ANOVA with Spatial compatibility (Compatible and Incompatible) as a factor. Violations of the assumption of sphericity assessed by Mauchly's Test of Sphericity were in all ANOVA corrected for by using Greenhouse-Geisser corrections. All *post-hoc* analyses were performed with a Bonferroni correction.

13.3 | Results

Subjective Visual Vertical test

In the Subjective Visual Vertical test, the participants' orientation elicited statistically significant changes in participants' confidence ($F_{3.2,161.9} = 50$, $p < .001$, $\eta_p^2 = .49$, Figure 52a), response times ($F_{3.4,172.2} = 10.3$, $p < .001$, $\eta_p^2 = .17$, Figure 52b), and accuracy ($F_{2.9,148.4} = 3.2$, $p = .027$, $\eta_p^2 = .059$, Figure 52, c). *Post-hoc* analyses revealed that participants were less confident when tilted ($p < .001$), and that participants were more confident when tilted 12° to the left than when tilted 12° and 24° to the right ($p < .001$ and $p = .007$ respectively). They also had longer response times when tilted to the right and to the left ($p < .001$ and $p < .01$, respectively) and had a decreased accuracy when tilted to the right only ($p = .05$).

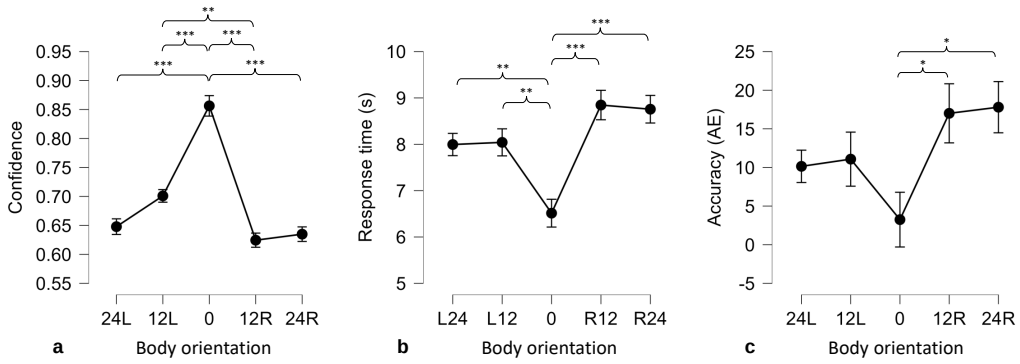

Figure 52: Results of SVV test. Effect of the body tilt on **a** confidence, **b** response time, and **c** accuracy. Accuracy corresponds to the absolute angle error (AE) for indicated orientations. Error bars represent the standard errors ($^{***}p < .001, ^{**}p < .01, ^{*}p < .05$).

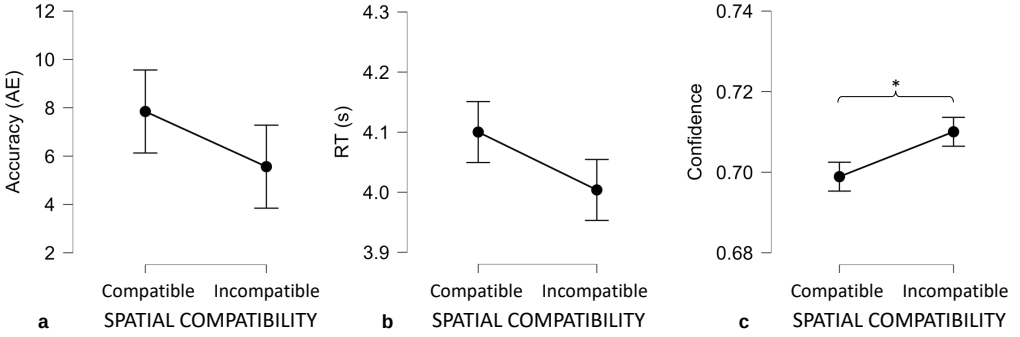

Figure 53: Results of the perception task. Effect of body tilt and object orientations compatibility on **a** accuracy, **b** response time, and **c** the confidence participants had in their responses. Accuracy corresponds to the angle error (AE) for indicated orientations. Error bars represent the standard errors ($^{*}p < .05$).

Effect of tilt compatibility – Perception task

In the perception task, the compatibility between participant and object tilts elicited statistically significant changes in confidence ($F_{1,53} = 4.8$, p = .033, η_p^2 = .087, Figure 53c). Participants were less confident during compatible conditions. However, no significant main effect of compatibility was found for accuracy (Figure 53a) nor response time (Figure 53b).

Effect of movement compatibility – Manual-control task

In the manual-control task, the compatibility between participants' whole-body and manual movements elicited statistically significant changes in their accuracy ($F_{1,53} = 10.7$, p = .002, η_p^2= .168, Figure 54a), precision ($F_{1,53} = 4.57$, p = .037, η_p^2= .079, Figure 54b), and response times ($F_{1,53} = 4$, p = .049, η_p^2 = .071, Figure 54c). Incompatible conditions induced

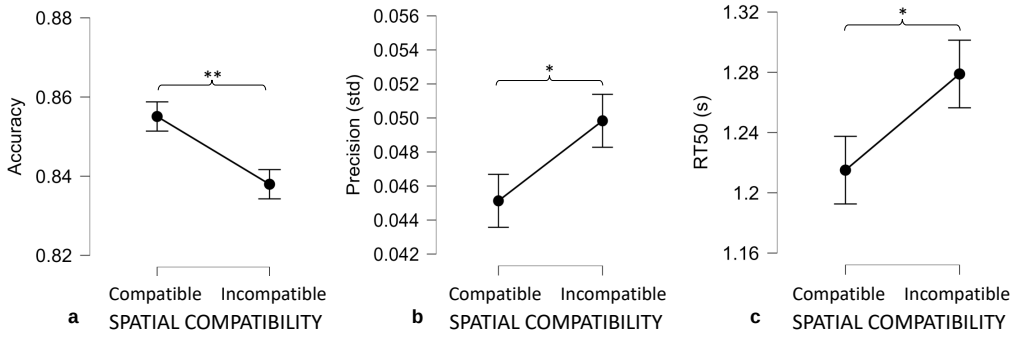

Figure 54: Results of the manual-control task. Effect of whole-body and manual control movements compatibility on **a** accuracy, **b** precision, and **c** response time. The accuracy corresponded to the normalized average angle of the panel during the last 5 seconds of the trial, i.e. 1 corresponds to the target angle. Precision corresponds to motor responses' standard deviation during manual control during the last 5 seconds of the trial. RT50 corresponds to the time to reach 50% of the final response angle. Error bars represent the standard errors ($^{**}p < .01, ^{*}p < .05$).

decreased accuracy and precision, and participants took longer to reach 50% of their response angle during the remote operation of the rover's panels. However, no significant main effect of compatibility was found regarding the time participants took to start the manual movement ($F_{1,53} = 1.75$, $p = .19$, $\eta_p^2 = .032$).

13.4 | Discussion

In this study, we applied the improvements identified following our first pilot study. This updated version of our paradigm allowed us to investigate how spatial (in)compatibilities between the direction of participants' body roll tilts and motion, and that of the teleoperated unit, could affect manual control, perception, and confidence during teleoperation in virtual reality. The main results revealed that, as expected, spatial incompatibilities between participants' whole-body and manual movements negatively impacted their teleoperation performance (accuracy, precision, and response times). In addition, body roll tilts decreased the confidence participants had in their visual perception of the remotely controlled object, but surprisingly, only in the compatible conditions. Yet, contrary to our hypotheses, spatial incompatibility did not affect the perception of the orientation of the teleoperated object per se. These results, their implications, and their limits are further discussed below.

SVV results The SVV results validated our setup's operability (correct functioning) with respect to alterations of the participants' vertical perception. The scores did not result in the exclusion of any participants due to inner ear damage. Although no specific hypotheses were formulated regarding the SVV, our findings revealed an interesting pattern of left-sided spatial bias among the participants. When asked to judge the orientation of the

vertical while being tilted at several angles (SVV test), participants were faster and more confident in their responses when tilted to the left. These results are consistent with previous studies that highlight the observation of a leftward bias in healthy participants during visuospatial tasks, known as the pseudo-neglect phenomenon (Brooks et al., 2014).

Effect of spatial compatibility on the manual control of the teleoperated object In accordance with our hypotheses, the spatial incompatibilities between body and manual control movements during teleoperation affected teleoperation performance. Incompatibilities in movement resulted in participants being less precise, less accurate, and taking more time to complete the initial phase of the manual movement. To the best of our knowledge, no previous study had precisely investigated how compatibility between whole-body rotation and manual control movement direction impacts teleoperation. These results are consistent with Simon and Craft (1970) and show that an irrelevant body movement distraction could also impair manual control precision, accuracy, and response time. Note that our protocol does not allow us to determine whether this decrease in performance is due to a decrease in visual perception of the teleoperated object leading to an unadapted motor command; or if it is due to the centrifugal force exerted on the actuator that the participant has to compensate during manual/thumb control (or a combination of both).

Effect of spatial compatibility on the teleoperated object orientation estimation Contrary to our expectations, spatial incompatibilities between body tilt and the remotely controlled object's orientations did not affect participants' orientation estimation, neither in terms of accuracy, nor response times. However, being tilted did influence participants' post-choice confidence in the orientation estimation task, yet surprisingly only during compatible conditions. Lipshits et al. (2005) studied the oblique effect (i.e., the human tendency to better perceive vertical or horizontal visual stimuli compared to the oblique ones) in several body orientations close to ours (22.5° inclination to the vertical). The results showed that only the perception of vertical and horizontal orientations (with the head/body axis as the frame of reference) was impaired when the participants were tilted. However, oblique lines were perceived equally well when participants were tilted and upright, which could explain the results of the present study. Indeed, in our analyses, we compare conditions where the panels were systematically oblique (with the head/body axis as the frame of reference). Authors explain these phenomena by the fact that the perception of orientations will be stored in both an egocentric frame of reference (linked to the axis of the body) and an allocentric frame of reference (linked to the perceived axis of gravity) when available. When the body is in a natural upright position, both reference frames are aligned. However, once the body is tilted, a conflict occurs between these two frames, which can result in uncertainty in the representation of vertical and horizontal orientations. Furthermore, it is important to note that in our study, the body tilts did not exceed 24° which corresponds to a small tilt in comparison with other studies where the authors used 45° (Bernard-Espina

et al., 2022; Fraser et al., 2015) or 90° (i.e supine, ventral or lateral lying positions) tilts (Dyde et al., 2006; Kim et al., 2022; Mast et al., 2003; Miwa et al., 2019; Schuler et al., 2010).

Confidence results Post-choice confidence represents the probability that the perceptual decision is correct based on available sensory evidence. Drugowitsch et al. (2014) found that '*bounded evidence accumulation explains decision accuracy, speed, and certainty*.' Although a tilted participant wearing a head-mounted display (aligned with their head as a frame of reference) already experiences sensorial conflict, we hypothesized that under incompatible spatial conditions, the visuo-vestibular/somatosensory conflict would further challenge the visual afferents leading to a larger decrease in confidence. We did observe a compatibility effect, but unexpectedly, participants showed a decreased confidence only when the body and the object were tilted in the same direction (i.e. compatible conditions). The analysis of the collected data highlighted several limitations. In Simon's studies (Simon and Rudell, 1967), the effect of compatibility occurs when the spatial position of the stimulus and the required response were compatible. Regarding the perception task of our protocol, the spatial compatibility of the different aspects of the task that were supposed to be compatible or incompatible may be perceived as ambiguous. One could argue that when the panels were oriented to the right, it had to be aligned with the left rod, and that the reproduction of the panels' perpendicular instead of their actual orientation could lead to a small conflict. However, the instructions given to the participants were to align the panels with the A, B or C rod (Figure 48A), thus the rods' laterality was never mentioned and the participants succeeded in performing the task as indexed by their accuracy, precision, and response times. Future studies using this experimental protocol must take these facts into account and modify this task to simplify the instructions. For instance, to limit these spatial incompatibilities and to have accurate compatible and incompatible conditions, the arrow could be replaced with a line and participants could be asked to reproduce the perceived orientation (and not the perpendicular).

General limitations The present study has other more general limitations that should be taken into consideration when interpreting the results. A first limitation is that our study group was not homogeneous, as there were only a few women (N=12) and left-handed (N=4) individuals. Furthermore, even though subjects understood the SVV task, the use of a simple rod instead of the human figure, as typically done in standard SVV tests, could have reduced the risk of misinterpretation regarding what the figure should align with—whether it be the body or the vertical axis. In addition to the limitations mentioned in the discussion of the panels' orientation perception task results, we also did not consider the possibility that the afterimage of the stimulus may still be present on the retina. In a protocol asking for memorization and reproduction of visually perceived orientation similar to ours, the authors addressed this issue by displaying a distractor image consisting of many crossing lines at different orientations presented for 1 s between stimulus transi-

tions Lipshits et al. (2005). The fact that subjects must, within a trial, first orient and then perceive the panels placed at the same angle, could facilitate the perception of orientation since it was manually controlled at that angle beforehand. Finally, our protocol separately investigates the effect of orientation on perception and movement on a visuomotor control task; it might be interesting to study whether perception can be impacted by movement and if inclination alone could also affect manual performance during teleoperation tasks.

HIGHLIGHTS

1. In conclusion, after improvements, this new paradigm demonstrated that the spatial (in)compatibility effects observed in the literature can be transferred to the control of a distant robot in virtual reality.
2. Our results showed that spatial incompatibilities between body rotation and manual movement directions could impact participants' control of the remotely operated robot in response time, accuracy, and precision while controlling the robot's orientation.
3. Surprisingly, participants' post-choice confidence in the robot's perception decreased in the spatially compatible condition.

14 | Chapter conclusion

This first experimental block aimed to evaluate the manifestation of spatial (in)compatibility effects between the direction of the operator's body and the robot's tilt and motion on teleoperation performance. It aimed to address two key questions:

1. Does spatial incompatibility between the direction of the operator's body tilt and that of the robot impact the perception of the robot?

2. Does spatial incompatibility between the direction of the operator's body motion and the manual movement performed impact the control of the robot?

Although we did not observe a spatial (in)compatibility effect between the direction of the operator's body tilt and that of the robot on the perception accuracy of the robot, this new paradigm demonstrated that the spatial (in)compatibility effects regarding motion directions can affect the control of a robot in virtual reality. Indeed, it showed that spatial incompatibilities between body rotation and manual movement directions could significantly impact participants' control of the remotely operated robot, affecting both response

time and accuracy during orientation control. Furthermore, and contrary to our expectation, body tilt influenced participant' post-choice confidence in their perception but only in the compatible spatial condition. These results can, however, be explained by the experimental limitations of the perception task.

In these first experimental studies, the design was highly controlled, in that the teleoperation task involved only controlling the orientation of a part of the robot, discontinuously, trial by trial. Additionally, in this teleoperation scenario, the robot was static in the distant environment and visualized from a third-person perspective. Therefore, in our next study, we aim to investigate whether these effects of operator motion also transfer to a more dynamic and continuous task, such as one requiring the continuous control of a robot performing navigation in the distant environment, block by block rather than trial by trial. We also intend to compare teleoperation performance between conditions with and without motion. Finally, we will address the topic of interfaces and investigate whether one type could mitigate the observed effects.

IV. Effects of teleoperator motion and proposition of adapted visual interfaces

The first study of this manuscript (Exp I) revealed that spatial incompatibility between the motion direction of the operator's body and the manual movements used to orient the teleoperated unit negatively affects manual control in virtual reality. In this chapter, we explore whether these spatial incompatibility effects also extend to navigation tasks requiring more continuous control in virtual reality. Furthermore, building on our initial study, we compare teleoperation performance in dynamic and static environments, while examining the suitability of visualization interfaces for these dynamic settings.

To address these questions, an experimental protocol was designed to answer the following three research questions:

1. Does the operator's body motion impact teleoperation compared to a static condition?

2. Does spatial incompatibility between the motion directions of the operator's body and that of the controlled robot further impact teleoperation?

3. Does the type of visualization interface reduce or compensate for the negative effects related to the operator's body motions?

Similar to the previous chapter, a pilot study was conducted, leading to significant changes to the protocol before carrying out a larger-scale study. The pilot study presented in this section was published in an international conference's proceedings (i.e. *Human-Robot Interaction 2024*) and later showcased as a poster.

15 | The pilot study

15.1 | Introduction

In our first study (Exp Ib), we focused on the manifestation of a spatial compatibility effect in teleoperation tasks conducted from a dynamic environment and observed a spatial incompatibility effect between the direction of body motion and manual motion during the control of the robot. Our participants showed decreased precision and accuracy and slower reaction times (RT) when performing in spatially incompatible motion directions. The goal of this new experiment is to deepen our understanding of this spatial (in)compatibility effect on manual control to see if it also transfers to a different teleoperation task. We will also compare the results with teleoperation conditions without body motion to address the first research question of this thesis: whether a dynamic environment, compared to a stable one, affects teleoperation, as this question remains unanswered in our first chapter.

The nature of the teleoperation task has been revised for this new experiment. In Exp Ib, the task consisted solely of controlling the orientation of a part of the robot, in particular the solar panels of a static rover. In this new study, the task will still focus on the perception and control of orientations, as the literature has shown that these performances tend to be most affected by altered force fields (Section 8). However, this time, it will be within the context of a navigation task in a remote environment. Also, unlike the previous task, this new one will be continuous. Indeed, in the "Manual-control task" from Exp Ib, the goal was to orient a panel to a target angle, trial after trial. Once the angle was reached, the trial ended. For this new task, we have chosen to move towards a more continuous control paradigm that is more representative of real-world teleoperation scenarios. Control will be continuous across blocks consisting of several trials. During each block, participants will need to adjust the robot's orientation throughout an obstacle course. This paradigm shift allows us to assess whether the spatial (in)compatibility effects we observed in the manipulation of a part of a fixed robot (Exp Ib) transfer to longer and more complex navigation tasks.

Furthermore, in this chapter, we address the topic of visual interfaces and investigate whether one type of visualization could mitigate the observed effects. Indeed, as seen in Section 4.6, research dedicated to ergonomics in video games and teleoperation indicates that different visualization types could significantly enhance users' situational awareness and performance. For instance, the way to present attitude information in a navigation task involving a flying vehicle, like piloting an aircraft, has consequences on pilots' spatial orientation. Müller et al. (2018) compared two types of attitude indicators (AI): the moving-horizon (MH) format and the moving-aircraft (MA) format, corresponding to the standard AI formats used in Western and Soviet aviation, respectively. They presented different theories indicating that the MA format would be more intuitive and enhance spatial orientation during piloting. They also investigated to what extent the superiority of the MA format over the MH format in maintaining spatial orientation persists with cur-

rent primary flight display technology. Their findings revealed that both novice and expert pilots demonstrated improved performance when using the MA AI format in tracking and recovery piloting exercises conducted in a PC-based simulator. Furthermore, studies demonstrated that in VR, dynamic tasks involving operator motion or interaction with moving objects show that the third-person perspective (3PP) could significantly enhance user performance (Bhandari and O'Neill, 2020; Temma et al., 2019; **?**; **?**). On the contrary, the first-person perspective (1PP) was found to be preferable when interacting with static objects directly in front of users (Alonso et al., 2016; Bhandari and O'Neill, 2020; Salamin et al., 2006). The 3PP is integrated into the typical egocentric visualization when controlling UAVs and UGVs to enhance operators' spatial awareness (Erat et al., 2018; Kelly et al., 2011; Saakes et al., 2013; Saitoh et al., 2006; Temma et al., 2019; Thomason et al., 2017). If degraded performance is observed due to operator motions, we suppose that certain types of visualizations could compensate for the observed negative effects.

The assessment of a teleoperation system's effectiveness also involves evaluating the user's subjective experience (Section 3, (Brooke et al., 1990)). In our first study, the operator's subjective experience was only recorded for the perception task, specifically a measure of post-perceptual confidence. However, no subjective performance measures were collected for the robot control task. For this experiment, we chose to gather a measure of workload, a measure commonly used in ergonomics and human factors domains in human-robot interaction to assess the demands placed on an operator by a task (as explained in Section 3.2). We selected three items from the NASA-TLX questionnaire, considered the most relevant for our research questions: perceived mental demands, frustration, and perceived task difficulty. We decided not to administer the full questionnaire at the end of each block to avoid having participants spend more time completing the questionnaire than performing the task itself.

To address these research questions, we designed and tested the first version of an experimental protocol in Virtual Reality that aimed to compare participants' drone teleoperation performance and mental workload under different view perspectives (first-person-perspective vs. third-person-perspective) and attitude display types (fixed wing vs. fixed horizon) visual conditions, while operators' bodies were either stationary or in motion under spatially compatible or incompatible conditions with respect to drone movements. We hypothesized a degraded performance and increased workload in the presence of any motion. These effects should be stronger for incompatible motions compared to compatible motions. Based on the literature, we expected an increased performance and a decreased workload when operators teleoperate with a 3PP view and in a fixed horizon (MA) type of attitude visualization for all chair conditions.

15.2 | Methods

Participants

A total of 11 healthy volunteers participated in the study (7 females, mean age = 24.08 ± 4). Participants had normal or corrected-to-normal vision, no history of neurological, psychiatric diseases, or severe motion sickness, and were free of the regular use of medication.

Ethics statement

All participants were informed of their rights and gave their written informed consent for participation in the study before the experiment, according to the Declaration of Helsinki. The research was carried out by fulfilling ethical requirements following the standard procedures.

Experimental device

The study was conducted in the VR research room. Participants were placed on a motion platform (VRtigo 6-axis movement platform, PS-6TM-150, MotionSystems), in a dark environment, equipped with a VR headset (HTC Vive Pro) and the gamepad Logitech F310 on their lap. The tasks were implemented in Unity3D / *C#*.

Study design and procedure

During the experiment, participants were asked, under various conditions, to pilot a virtual drone using a head-mounted display (HMD) across islands in a VR environment.

The courses The objective of the participants was to pilot a drone through three different courses, each located on an island in the VR environment. They moved from one island to another through a teleport gate located at the end of each course on the other side of the island. The participants had to fully complete each course by performing transverse, vertical, and mixed maneuvers while crossing arches and hoops. The goal was to finish the course as quickly as possible by passing through all the arches and hoops while avoiding collisions as much as possible.

The teleoperation environment in VR The movements of our drone in VR replicated those of a real drone. The right joystick controlled the drone's forward/backward movements with vertical thumb motions (pitch control) and managed its yaw rotations with horizontal thumb movements (roll control). Meanwhile, the left joystick handled the drone's horizontal translations with horizontal thumb adjustments (roll control) and its vertical movements with vertical thumb motions (pitch control). Pretests revealed a high level of cybersickness and/or motion sickness, likely due to the robot being in motion while the operator was also in motion. To reduce the cybersickness observed in the pre-tests, we modified the VR environment so that participants were placed in a virtual room, facing a

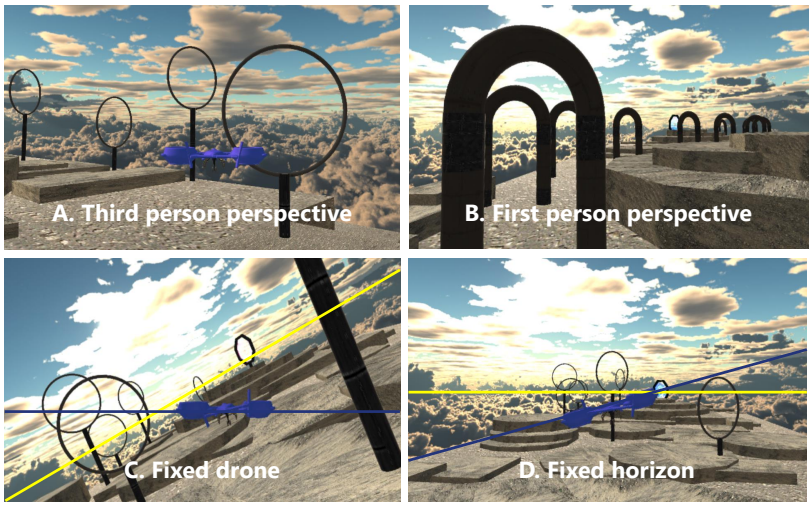

Figure 55: Visual conditions: Participants could control the drone with the A) third-person perspective or the B) first-person perspective, and the C) fixed-drone or D) fixed-horizon type of attitude visualization.

screen through which they could control the drone. This allowed us to decrease the field of view (FOV) and consequently reduce cybersickness symptoms, as "*using wider FOVs enables more prevalent optic flow in the user's peripheral vision, which commonly leads to cybersickness*" (Tian et al., 2022). Participants could not see their hands. Their head movements were integrated into the virtual world, meaning that when participants moved their heads, they could look behind them in the virtual room if they wanted to. However, the movements of the motion platform were not translated into the virtual world.

The visual interface conditions We presented the user's perspective in two distinct views (Figure 55A and 55B). The 1PP corresponded to a standard view in a VR HMD, where the operator saw the live video feed from the drone's onboard camera. In the 3PP, the operator viewed the drone and its surroundings from an external viewpoint. The camera view remained constant relative to the drone, corresponding to an egocentric 3PP. As the camera was virtually positioned behind the drone, the field of view was expanded, offering a more extensive visual perspective. Two different types of attitude displays were also presented (Figure 55C and 55D). In the fixed-wing attitude display type, the operator could perceive the drone's orientation through the movement of the horizon, while the drone's avatar remained stationary. On the other hand, in the fixed-horizon attitude display type, the drone's movement was perceived through its tilting, while the horizon remained unchanged.

The chair motion conditions The participants performed the task in 3 chair conditions: the neutral condition where the chair was stationary, or the spatially compatible and incompatible conditions where the movement of the chair could be synchronized and identical or synchronized and reversed to those of the drone, which was controlled by the operators.

Procedure Prior to the main task, participants completed a tutorial and training to familiarize themselves with the drone controls, the VR environment, and all visual conditions. The main task consisted of 12 trials, one trial per condition (2 perspective × 2 attitude display × 3 chair conditions) and lasted approximately 15 minutes. At the end of each trial, participants were required to report their levels of mental demands, frustration, and perceived task difficulty experienced during the trial (using NASA-TLX items to measure mental workload). In total, the experiment (tutorial, familiarization, and task) lasted 30 minutes. Each participant performed all combinations of conditions. The order of condition presentation was counterbalanced using the Latin square method.

Data processing and statistical analysis

We examined participants' course completions (i.e. the number of times participants successfully navigated through the entire course, passing all the required elements, such as hoops and arches), the number of collisions, task duration, as well as participants' responses to the NASA-TLX questionnaire (mental demands, task difficulty, and frustration). All 11 subjects were included in the analysis. Data were analyzed by a 3-way repeated measures ANOVA, with Greenhouse-Geisser sphericity corrections, with chair (Compatible, Incompatible, and Neutral), perspective (1PP, 3PP), and horizon (fixed-wing vs fixed-horizon) factors. All post hoc analyses were performed with a Bonferroni correction. All statistical analyses were performed using the JASP 0.18.3 software.

15.3 | Results

Number of collisions

There was no significant effect of Horizon or Chair, but results revealed a significant main effect of Perspective regarding participants' number of collisions ($F_{1,10} = 15.8$, $p = .003$, $\eta_p^2 = .613$). Participants made more collisions when controlling the drone in the 3PP in comparison with the 1PP, regardless of the attitude display and chair conditions (Figure 56A).

Course completion

There was no effect of Horizon, Perspective or Chair regarding course completions, but a statistically significant interaction between **Chair** and **Perspective** was found ($F_{1,10} = 3.7$,

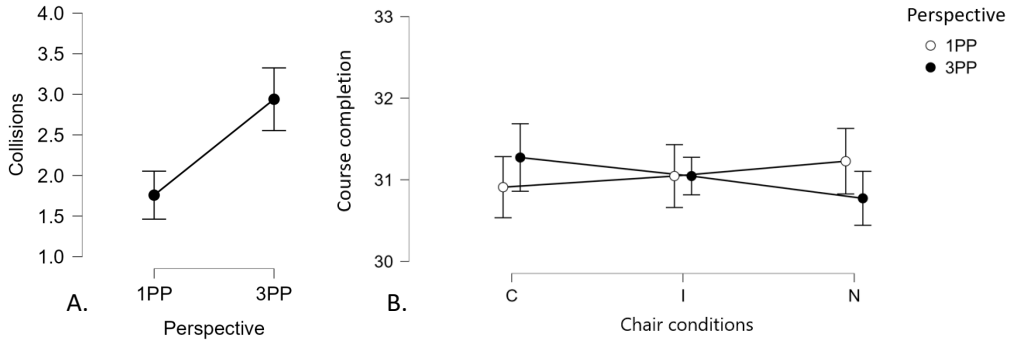

Figure 56: A. Impact of Perspective on the number of Collisions and B. Interaction between Perspective and Compatibility of chair and drone motion directions on Course Completion.

p = .043, η_p^2 = .003). When the chair motions were spatially compatible with those of the drone, participants showed an increased performance in the 3PP in comparison with the 1PP. However, when the chair was static results were reversed and participants showed a better performance in the 1PP than the 3PP (Cohen's D equals, respectively, -0.402 and 0.503, Figure 56B). There was no difference in performance between the perspective views when the chair motions were spatially incompatible with those of the drone.

All other analyses related to task duration and the NASA-TLX questionnaire (mental demands, task difficulty, and frustration) yielded no significant results.

15.4 | Discussion

In this preliminary study, we compared operators' drone teleoperation performance in Virtual Reality under different view perspectives (1PP vs. 3PP) and attitude display types (fixed-wing vs. fixed-horizon), while operators' bodies were either stationary or in motion under spatially compatible and incompatible conditions with respect to the drone's movement.

What's of particular interest in our results is that when operators remained in the 1PP, we observed a decrease in their course completion performance as soon as the chair was in motion. However, when they shifted to the 3PP, their performance equaled or exceeded that of the 1PP visual condition. These results suggest that during navigation tasks, an operator's motion differently impacts their performance in function of the perspective views. According to this measure, the 3PP vizualization is better suited for teleoperation in a dynamic environment. This is consistent with previous studies (Bhandari and O'Neill, 2020; Erat et al., 2018; Kelly et al., 2011; Saakes et al., 2013; Saitoh et al., 2006; Temma et al., 2019; Thomason et al., 2017; **?**; **?**). However, our findings deviated from our initial expectations regarding the impact of perspective on participants' teleoperation performance. Indeed,

based on the literature, we hypothesized that the 3PP would enhance spatial orientation, leading to better performance in navigation tasks. On the contrary, our results show that participants made more collisions in the 3PP compared to the 1PP. Yet studies suggested that the optimal perspective in VR is task-dependent and literature has shown that the 1PP provides a higher sense of embodiment, particularly beneficial for navigation tasks in VR (Alonso et al., 2016; Medeiros et al., 2018).

Limitations and prospects for improvement

Effect of the horizon-type display Our study did not reveal any significative effect or interaction of the horizon-type display. We speculate that this could be because the primary distinction between these visualizations lies in the way lateral and frontal tilts of the drone are displayed. To align closely with operational reality, we replicated the same flight and camera stabilization parameters of the DJI FPV drone in VR. To maintain a fixed image, as soon as an inclination is perceived, whether lateral or frontal, the camera compensates by tilting in the opposite direction. As a result, the robot's tilts are only minimally reflected in the participant's HMD when navigating in VR. **For a future study, an idea would be to use a virtual robot capable of lateral tilting to analyze this visual effect.**

Ambiguous spatial (in)compatibility conditions As mentioned previously, we aimed to replicate a control and a behavior similar to that of a real drone. To achieve this, when the drone moves forward, it tilts forward. In the compatible condition, the chair's motions are synchronized with those of the drone, resulting in a forward tilt of the chair. Conversely, in incompatible conditions, this results in a backward tilt of the chair. What we did not anticipate at the time is that a backward tilt (in the incompatible condition) is much more representative of the effects of acceleration typically experienced in a vehicle (in terms of vestibular and somatosensorial perceptions). As a result, our incompatible condition likely suggested a forward acceleration perception to the operators' internal graviceptive systems, which could have reduced intersensory conflict and possibly improved performance. **To address this, one solution will be to avoid synchronizing the robot's motions with those of the chair (see explanation below) and, importantly, to design a task that requires only lateral tilting (on the roll axis) to prevent the illusion of acceleration and deceleration.**

The problem of synchronizing chair and robot motion We wanted to study the effect of spatial compatibility when the motions of a vehicle are spatially compatible or incompatible with those performed to control the remote robot. A relatively simple way to reproduce compatible and incompatible motion conditions, given our equipment, was to synchronize the vehicle's motions with those of the chair and to reverse them for incompatible motion conditions. Upon reflection, it became clear that synchronizing the drone's motions

with those of the chair was a mistake. Indeed, an important characteristic of the dynamic environments we are interestedin is the unpredictable nature of the vehicle's motions. If the participant is responsible for the chair's motions, as in this study, we deviate from the context we intended to study. Our participants were not able to discern whether the motion was compatible or incompatible, but they were acutely aware that the motions they performed on the chair would be replicated in occurrence and magnitude throughout the experiment. Moreover, based on observations of the experimental sessions, this likely affected the motions required with the drone, depending on their appreciation (or not) of the chair's motions. **For the next study, it would be preferable to induce spatial compatibility conditions without synchronizing the robot's motions with those of the participant's chair. This could be achieved by designing situations where the operator must tilt a robot in a specific direction, to navigate around an obstacle for instance, allowing to program the chair's motions to create compatible and incompatible conditions without relying on the robot's motions performed by the participant.**

Sample size Finally, due to the relatively small size (n=11), it is important to approach the results of this preliminary study and their interpretation with caution. Additionally, our participants did not all have the same level of experience with video games. As a result, the task might have seemed too simple for some and much too complex for others, which could have affected our results. **Several options exist to address these limitations. If we want to keep a task that is more representative of drone piloting and maintain the same control options, it is necessary to measure participants' levels of drone and video game experience and include these as covariates in our analyses. Another option would be simplifying the robot control to make the task accessible to a broader audience. Finally, increasing the size of the study group would also be beneficial.**

HIGHLIGHTS

1. These preliminary findings suggest that teleoperation from dynamic environments could decrease operator navigation performance.
2. The 3PP appears to mitigate these negative effects.
3. However, this pilot study has significant experimental limitations that must be considered before providing answers to our research questions.

16 | The main study

16.1 | Introduction

All of the prospects for improvement mentioned in the discussion of our pilot study have been considered and applied to this study. (1) Therefore, the teleoperation task in this revised study involves controlling the lateral tilt of a spaceship-type robot that automatically moves along a path filled with obstacles that must be avoided. (2) Spatial (in)compatibility conditions between the robot's motions and those of the chair have been created, as discussed, by requiring participants to perform tilts in a specific direction along the roll axis. We only needed to create chair motions that were either compatible or incompatible with the tilt direction required to navigate around the obstacles. (3) Although our pilot study results were inconsistent depending on the measure used, we observed an interesting effect related to the participant's visual perspective during teleoperation. As a result, we decided to focus on testing only the impact of visual perspective on teleoperation performance and user experience. Indeed, although we could have re-evaluated the visual display effect (especially since we found a method to include lateral tilts this time), we decided to simplify the experiment and ensure more reliable statistical results by limiting the number of conditions.

In this updated version, we decided to add and change the subjective measures. (4) Because both the operator and the robot are in conflicting motions, the risk of experiencing motion sickness and cybersickness increases significantly. Given the various types of symptoms and their impact on cognitive abilities and participant well-being (Section 8), we believe it is essential to measure the level of these symptoms in our participants, as they could influence our results and are a crucial part of the user experience in a teleoperation system. This will allow us, for example, to determine whether a particular type of visualization could reduce these symptoms, which are known to affect operator performance in moving vehicles (Section 8). (5) Secondly, to obtain a more representative subjective measure of the mental and physical dimensions of workload, we have chosen to replace the NASA TLX questionnaire (Hart and Staveland, 1988b) items previously used (Frustration, Effort, and Performance) with the "Mental demands" and "Physical demands" items of the same questionnaire, which will be associated with questions about motion sickness.

(6) Furthermore, numerous studies have observed interindividual differences in the way humans process the internal graviceptive and visual information when estimating the orientation of the vertical (perceptual style), especially when there is a conflict between visual and internal (vestibular and somatosensory systems) cues, in the Rod and Frame Test (Oltman, 1968). Some individuals accurately perceive the conflict and, therefore, adapt by reweighting sensory inputs. They give more importance to those that are relevant to the task at hand, which increases their performance (field-independent). Others, however, fail to notice the conflict and tend to be influenced and biased by their visual information,

which impairs their perception of the vertical (field-dependent) (Isableu et al., 2010). If such profiles exist, it would imply that, potentially, certain individuals, field-dependent individuals, might have more difficulty inhibiting irrelevant gravitational information for the task and, as a result, be more impacted than others during teleoperation in a dynamic environment. Therefore, we believe it is necessary to control this variable in our studies. One way to assess these profiles is to compare our participants' results on the Rod and Frame Test, originally developed by Witkin and Asch (1948) and refined by Oltman (1968).

To summarize, the teleoperation task now involves navigating through rectangles while accurately replicating their tilt from different visual perspectives (1PP, 3PP), with the body either stationary or in motion, under spatially compatible or incompatible conditions (only in the roll axis). As in our pilot study, we expect a decline in performance, along with an increase in workload and motion sickness symptoms when any motion is present. These effects are anticipated to be more pronounced for spatially incompatible motions compared to compatible ones. We expect improved performance, along with reduced workload and motion sickness symptoms, when operators use a third-person perspective for all chair conditions. Furthermore, we anticipate that field-dependent individuals will be more affected by motion than field-independent individuals.

16.2 | Methods

Participants

A total of 37 healthy volunteers participated in the study (10 females, 4 left-handed, mean age = 32,87, SD = 10,54). Participants had normal or corrected-to-normal vision, no history of neurological, psychiatric diseases, or severe motion sickness, and were free of the regular use of medication.

Ethics statement

All volunteers were informed of their rights and gave their written informed consent for participation in the study, according to the Declaration of Helsinki. This work was approved by the Comité d'Éthique de la Recherche - CER at Université de Toulouse (CER number 2024-792).

Experimental device

The study was conducted in the VR research room within the French Aerospace Engineering School ISAE-SUPAERO. During this experiment, the participants performed two tasks in virtual reality. For both tasks, the participants were placed in a dark environment so that no visual cues could indicate their body orientation. The tasks were designed in Unity3D/*C#*.

For the first task (Rod and Frame Test – RFT), they sat on a chair, with a VR headset (HTC Vive Pro) and its controller. For the second task (teleoperation task), they used the same headset but were placed on a motion platform (VRtigo 6-axis movement platform, PS-6TM-150, MotionSystems) and used a gamepad (Logitech gamepad F310).

Study design and procedure

The study consisted of two virtual reality tasks (developed in Unity3D/C#). A Rod and Frame Test (RFT) developed by Maneuvrier et al. (2021) and a Teleoperation task that participants performed while seated on a motion platform. All visual presentations of tasks were egocentric; in other words, they were tilted with the chair rotation.

Rod and Frame Test To assess participants' perceptual style, we used the Rod and Frame test, a method originally developed by Witkin et al. in 1948 (Witkin and Asch, 1948) and refined by Oltman in 1968 (Oltman, 1968). Here we adapted the Maneuvrier Rod and Frame test (Maneuvrier et al., 2021) to suit the specific requirements of our study. The Rod and Frame Test was performed using the VR headset (HTC Vive Pro) and its controller. Participants were asked to "*align a red rod with the absolute physical vertical, parallel to a perfectly straight tree trunk.*" The rod to be oriented was placed inside a frame that could be tilted at different angles (-27°/+18°, -27/-18°, +27/-18°, +27°/+18° x 8 repetitions). To control the rod orientation, participants had to use the trackpad of the controller. To tilt the rod to the right, they pressed the right side of the trackpad, and to tilt it to the left, they pressed the left side of the trackpad. This test included 32 trials with a systematic counter balancing of the rod and frame rotation to eliminate order effects (Figure 57).

Teleoperation task The teleoperation task consisted of the piloting of a virtual spaceship using the same head-mounted display under different view perspectives (first-person-perspective vs. third-person-perspective) while their bodies were either stationary (Neutral condition) or in motion in a spatially compatible, incompatible, or mixed way regarding the ship's inclinations.

The task Participants were in charge of controlling the tilt of a spaceship as it autonomously navigated through obstacles. The objective was to adjust the spaceship's tilt to closely align with the tilt of the obstacle ahead (either to the right or left), aiming to minimize collisions. Feedback on their performance was provided at the top of the teleoperation interface. The Logitech gamepad F310 served as the controller. The right pad was used for the roll-tilt of the ship.

Visual perspective conditions We presented the user's perspective in two distinct views. The 1PP (Figure 58A) corresponded to a standard view in a VR HMD, where the

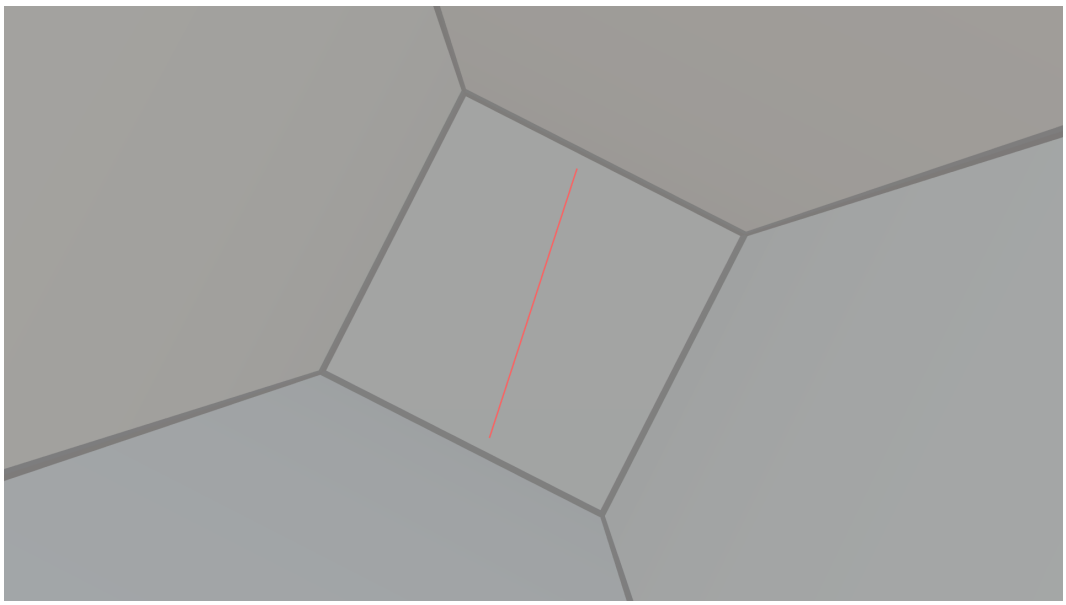

Figure 57: Rod and Frame test (RFT). First-person view of the virtual Rod and Frame Test at the beginning of a trial. Participants had to align the red rod, placed in the center of the frame, with the absolute physical vertical.

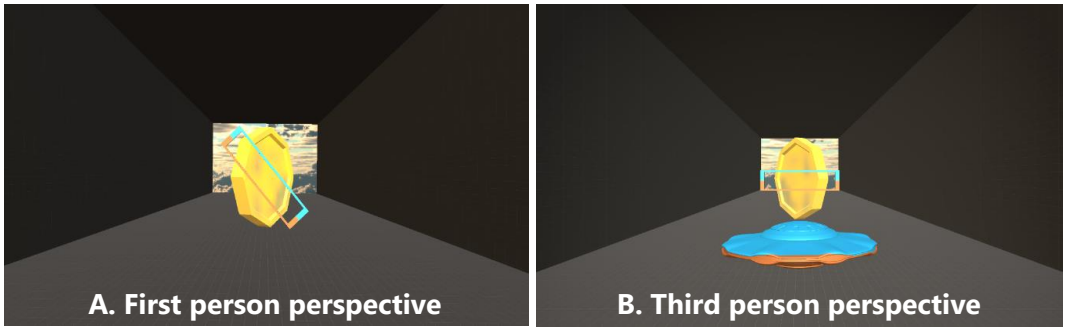

Figure 58: Visual conditions. Participants could control the spaceship at the A First-person perspective or the B Third-person perspective.

operator saw the live video feed from the drone's onboard camera. In the 3PP (Figure 58B), the operator viewed the drone and its surroundings from an external viewpoint. The camera view remained constant relative to the drone, corresponding to an egocentric 3PP. As the camera was virtually positioned behind the drone, the field of view was expanded, offering a more extensive visual perspective. Note that when the robot was tilted, the subjects perceived the robot tilting in a fixed remote environment.

Chair motion conditions The participants performed the task in four chair conditions: the Neutral (N) condition, where the chair was stationary; the Spatially Compatible (SC) condition, where the chair tilted in the *same direction* as the ship needed to clear the obstacle;

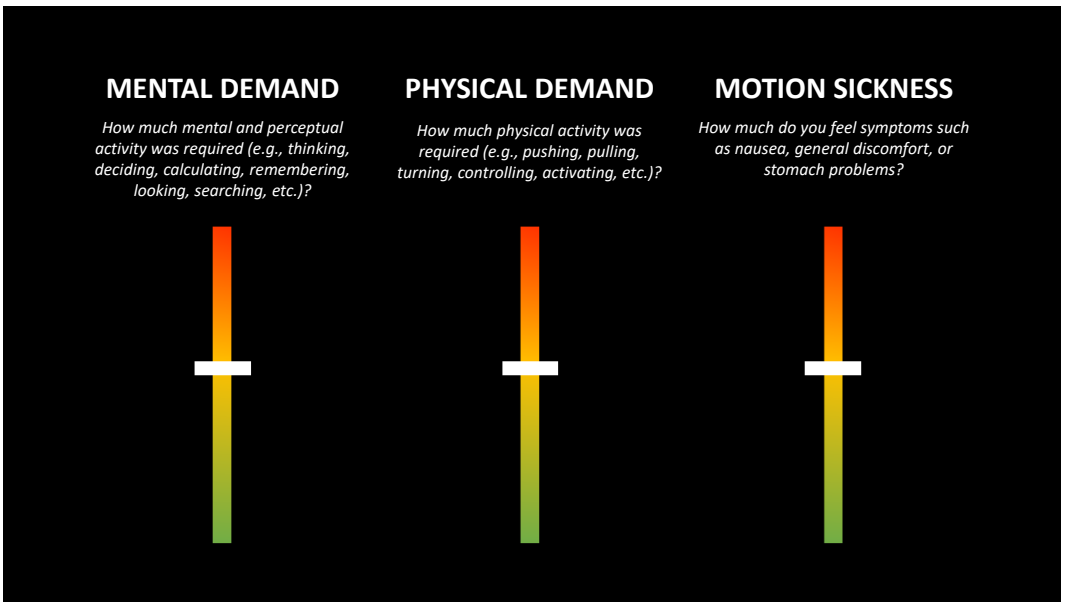

Figure 59: Items from the NASA-TLX questionnaire commonly used to assess mental, as well as a Fas Motion Sickness Scale from Keshavarz and Hecht (2011)

the Spatially Incompatible (SI) condition, where the chair tilted in the *opposite direction*; and the Mixed Motion (M) condition, where the chair tilted randomly in either the SC or SI direction. The chair roll-tilt started when the obstacle appeared to the participant and returned to its neutral/vertical position after the obstacle was passed.

Procedure Prior to the main experiment, participants completed a Rod and Frame Test, which included 32 trials. They then completed training to familiarize themselves with the ship controls, the VR environment, and all visual conditions of the teleoperation task. The task consisted of 20 blocks (5 chair motion conditions x 2 visual perspective conditions x 2 repetitions). Each block consisted of 14 trials, meaning that the participant navigated through 14 obstacles per block. The teleoperation task consisted then of 280 trials and lasted approximately 30 minutes. The order of block presentation was counterbalanced in a pseudorandom manner between participants. A trial consisted of piloting the ship in the VR environment under a set of conditions regarding view perspective and chair motion. At the end of each block, the subjects were asked to report their levels of perceived mental and physical demands (using NASA-TLX scales) as well as how many symptoms of motion sickness they felt during this trial (Fast Motion Sickness scale (FMS) from Keshavarz and Hecht (2011)), see Figure 59. Each participant performed all combinations of conditions.

Data processing and statistical analysis

Analysis of the effects of Chair motion and Visual perspective In our task, the ship was moving ahead at a constant speed, and participants only controlled the tilt. We, therefore, examined accuracy at the moment the ship encountered an obstacle (absolute error between the target angle and the angle achieved by the participant), the amount of motion per trial (sum of tilt changes between successive measurements), the quantity of overshoot in the other direction (area under the curve for the negative values, calculated from data normalized to the target angle) and the time taken to reach 10% and 50% of the target angle (kinematic measures). Additionally, we assessed participants' mental and physical workload, as well as motion sickness symptoms, through questionnaires (subjective measures). All 34 subjects were included in the analysis. Data were analyzed by a 2-way repeated measures ANOVA with Chair motion (Compatible, Incompatible, Neutral, and Mixed) and Visual perspective (1PP, 3PP) as factors. If Mauchly's test of sphericity indicated that the assumption of sphericity was violated ($p < .05$), degrees of freedom were corrected using Greenhouse-Geisser sphericity corrections. All post hoc analyses were performed with a Bonferroni correction. All statistical analyses were performed using the JASP 0.18.3 software.

Analysis of the effect of participants' perceptual style The analysis of the effect of participants' perceptual style on their teleoperation task performance was performed by adding the RFT results (angle error to the absolute vertical) as a covariate (scalar measure) in our three-factor based ANOVA analyses for each measure.

Analysis of the effect of block type Because we wanted to obtain subjective measures of mental and physical demands, as well as motion sickness, requiring a questionnaire response for each chair motion condition, especially for the spatial compatibility conditions, we designed our protocol with blocks of compatible chair motion conditions and blocks of incompatible chair motion conditions. However, the question of participants' habituation and possible anticipation of the chair motion within these blocks remains. To verify if there was any habituation within the blocks that might have impacted our results, we ensured that the Mixed condition (composed of compatible and incompatible trials) contained as many compatible and incompatible trials as the number of compatible and incompatible trials presented in the separate blocks, in order to perform additional analysis. We then compared only the compatible and incompatible data from the separate blocks and those from the mixed blocks in an additional ANOVA. As previously, data preprocessing was performed using Python programming. Data were analyzed using a 3-way repeated measures ANOVA with Chair motion (Compatible and Incompatible), Visual perspective (1PP, 3PP), and Block Type (Mixed and Non-Mixed) as factors. All post hoc analyses were per-

formed with a Bonferroni correction. All statistical analyses were performed using the JASP 0.18.3 software.

16.3 | Results

Accuracy (angle error)

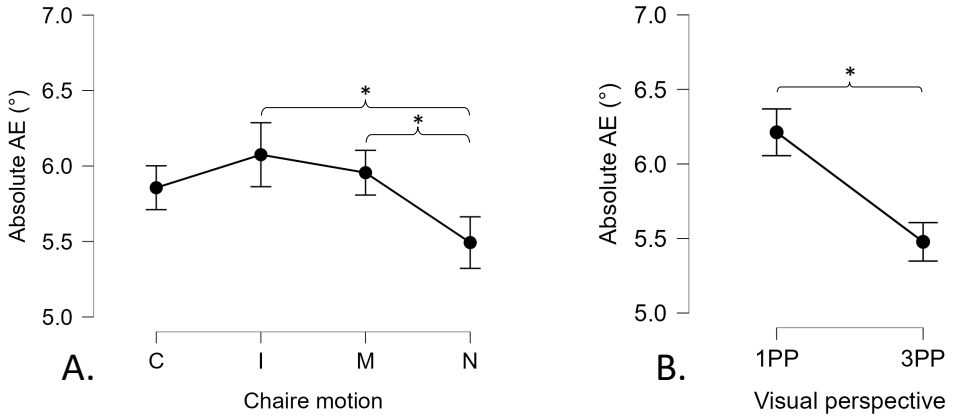

Figure 60: Effect of Chair motion (A) and Visual perspective (B) on participants' accuracy (absolute angle error). Error bars represent the standard errors (*p < .05). Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

There was a significant effect of both Chair motion (Figure $F_{2.516,90.558} = 4.804$, p = .006, η_p^2 = .118) and Visual perspective (Figure $F_{1,36} = 7.339$, p = .01, η_p^2 = .170) on the absolute angular error. Post-hoc tests revealed that the absolute errors were higher in the 1PP compared to the 3PP visual perspective (p = .01) and also higher when the chair motion was Incompatible (p = .003) and Mixed (p = .031) compared to when it was static (Neutral condition) (Figure 60).

To determine the direction of the error, that is, whether it was an overshooting or undershooting of inclination, we also examined the signed angular error. The analysis revealed a significant main effect of Visual perspective ($F_{1,36} = 11.124$, p = .002, $\eta_p^2 = .236$), and a significant interaction between Chair motion and Visual perspective ($F_{2.694,96.981} = 23.170$, p < .001, $\eta_p^2 = .397$). Post-hoc analysis showed that the 1PP-Compatible condition was significantly different from all others (all with p<.001, except 3PP, Incompatible where p=.042), except 1PP-Mixed, and that the 3PP-Compatible condition was significantly different from 3PP-Incompatible (p=.002) and 1PP-Mixed (p=.001) (Figure 61).

Quantity of movement

We measured the quantity of movement that participants exhibited in each trial during robot control. This was quantified as the absolute tilt difference between each point in

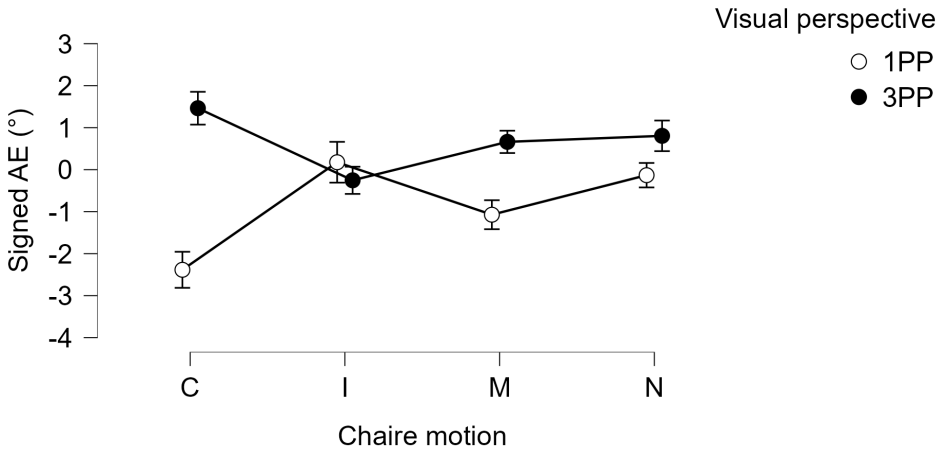

Figure 61: Interaction effect between Chair motion and Visual perspective on participants' accuracy (signed angle error). Positive values of AE correspond to overshooting, while negative values indicate undershooting. A mean signed AE near 0° means that participants were equally likely to overshoot and undershoot. Error bars represent the standard errors. Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

every frame across different conditions during the teleoperation task.

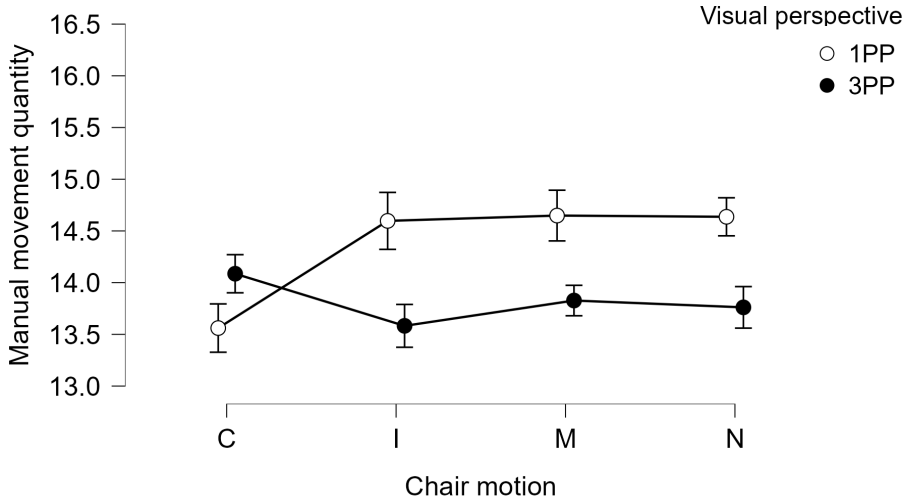

Figure 62: Interaction effect between Chair motion and Visual perspective on participants' manual movement quantity during robot control (in degrees). Error bars represent standard errors. Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

There was no main effect of Chair motion or Visual perspective on the participants' quantity of manual movement. However, a significant interaction between Chair motion and Visual perspective was found ($F_{2.092,75.303} = 12.572$, $p < .001$, $\eta_p^2 = .259$). The post hoc analysis showed that participants exhibited less manual movement during robot control

when in the 1PP and with spatially Compatible motion, compared to other motion conditions (1PP-Compatible was significantly different from 1PP-Incompatible, 1PP-Mixed and 1PP-Neutral, all with p<.001) (Figure 62).

Quantity of overshoot in the opposite direction

After visualizing our data, we observed that at the beginning of the trials, there was a notable tilt in the direction opposite to the target tilt of the trial, as shown in Figure 63. As mentioned in Section 8 (Chen et al., 2007), we hypothesized that this could be an overshoot in the opposite direction of the target angle due to the incompatible chair movement.

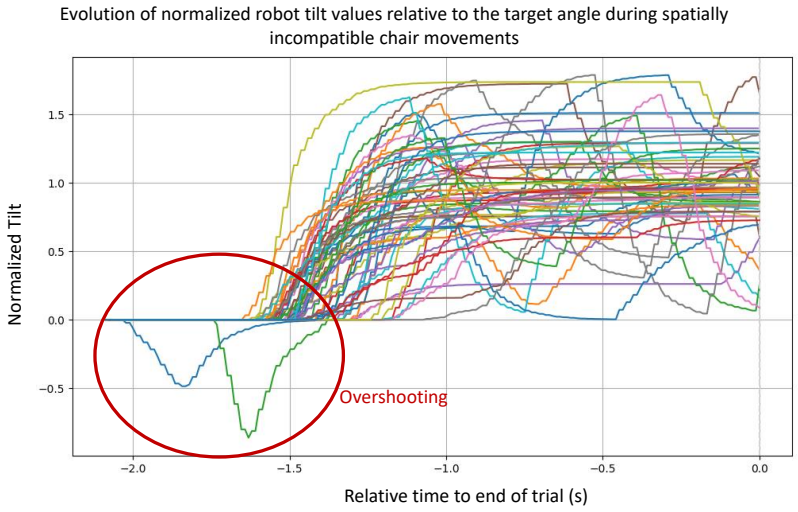

Figure 63: Illustration of the robot's normalized inclination values under a condition of incompatible chair movement. The graph highlights two overshoots, circled in red, occurring at the start of the test. These data represent the performance of a single participant.

Our results show no effect of Chair motion but reveal a significant effect of Visual perspective ($F_{1,36} = 10.715$, $p = .002$, $\eta_p^2 = .229$). In the 1PP, participants exhibit the greatest amount of movement in the opposite direction to the target angle (Figure 64).

Time taken to reach 10% and 50% of the target angle

In each trial, the subjects were required to reach a target angle within a defined time. One way to assess the timing of the subject's movement is to measure the time it takes them to reach a percentage of the target angle. Thus, we chose to assess the participants' time to reach 10% of the target angle (TTR10) to gauge the initiation of the manual movement, and their time to reach 50% of the target angle (TTR50) to measure the movement's progress over the trial.

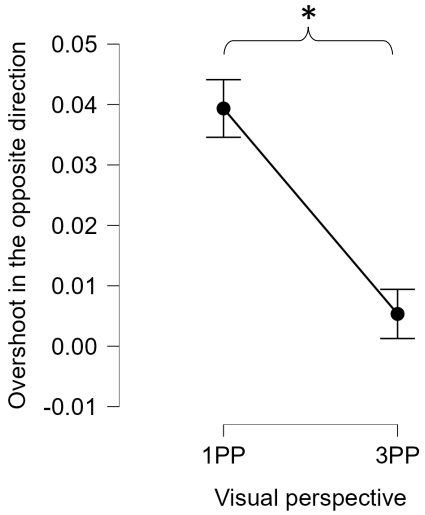

Figure 64: Effect of Visual perspective on the amount of overshooting in the reverse direction relative to the target angle. Error bars represent the standard errors (*p < .05)

TTR10 No main effects or interactions were found. However, a Chair motion effect was observed regarding participants' time to reach 10% of the target angle ($F_{1.962,70.628} = 7.898$, $p < .001$, $\eta_p^2 = .180$). When they were static, they took more time to reach 10% of the target angle; in other words, they took longer to initiate the movement (the Neutral chair condition was significantly different from Compatible (p=.011) , Incompatible (p=.001) and Mixed (p<.001)) Chair conditions, see Figure 65.

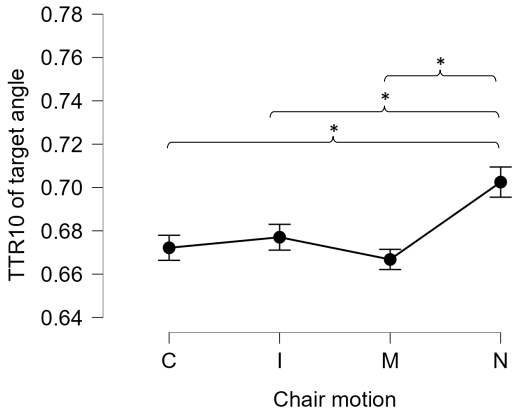

Figure 65: Effet of Chair motion on participant's time to reach 10% of the target angle (TTR10). Error bars represent the standard errors (*p < .05). Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

TTR50 A similar effect of Chair motion was found concerning the time to reach 50% of the target angle ($F_{2.257,81.265} = 8.253$, $p < .001$, $\eta_p^2 = .186$). In static conditions, participants took more time to reach 50% of the target angle (Figure 66A). Additionally, an interaction effect between Visual perspective and Chair motion was observed ($F_{2.62,94.308} = 3.904$, $p = .015$, $\eta_p^2 = .098$). This interaction indicates that in the 3PP, subjects took significantly more time to reach 50% of the target angle when static compared to when in motion (with p<.001 for Compatible and Mixed chair conditions and p=.043 for the Incompatible chair condition) (Figure 66B).

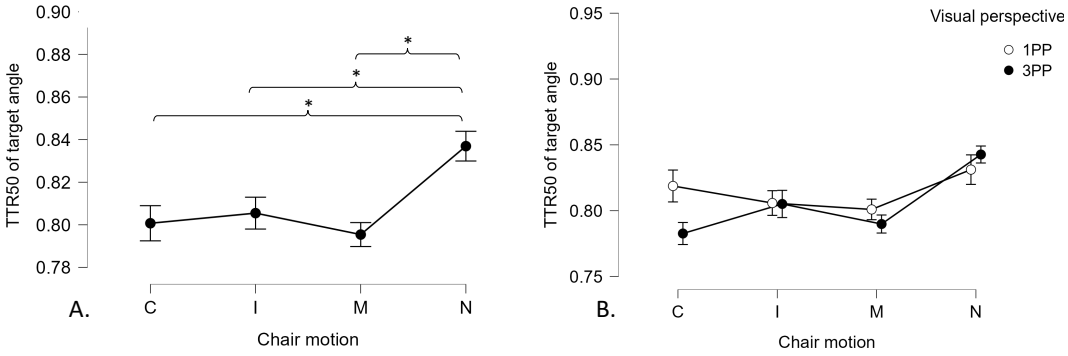

Figure 66: A. Effect of Chair motion on participant's time to reach 50% of the target angle, (*$p < .05$) and B. Interaction effect between Chair motion and Visual perspective on participants' time to reach 50% of the target angle. Error bars represent the standard errors. Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

Mental demands

Effects of both Chair motion ($F_{2.309,83.128} = 10.356$, $p < .001$, $\eta_p^2 = .223$) and Visual perspective ($F_{1,36} = 19.257$, $p < .001$, $\eta_p^2 = .349$) were found regarding the participant's perceived mental demands. Participants' mental demands were perceived higher in the 1PP (Figure 67A) and when in motion (Figure 67B), (the Neutral chair condition was significantly different from Compatible and Mixed with p=<.001, and from Incompatible chair condition with p=.004).

Physical demands

Effects of both Chair motion ($F_{1.521,54.772} = 22.547$, p< .001, $\eta_p^2 = 0.385$) and Visual perspective ($F_{1,36} = 9.837$, $p = .003$, $\eta_p^2 = .215$) were found regarding the participant's perceived physical demands. Participants' physical demands were perceived higher in the 1PP condition (Figure 68A) and when in motion (Figure 68B) (the Neutral chair condition was significantly different from all other chair motion conditions with p<.001).

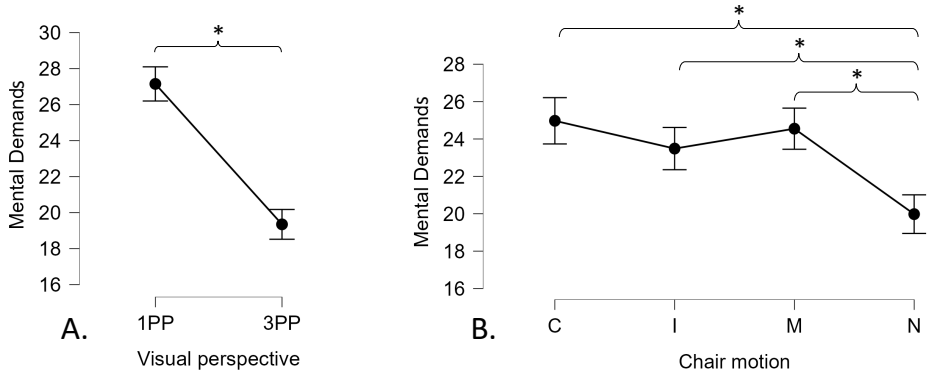

Figure 67: Effect of Visual perspective (A) and Chair motion (B) on participant's perceived mental demands. Error bars represent the standard errors (*p < .05). Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

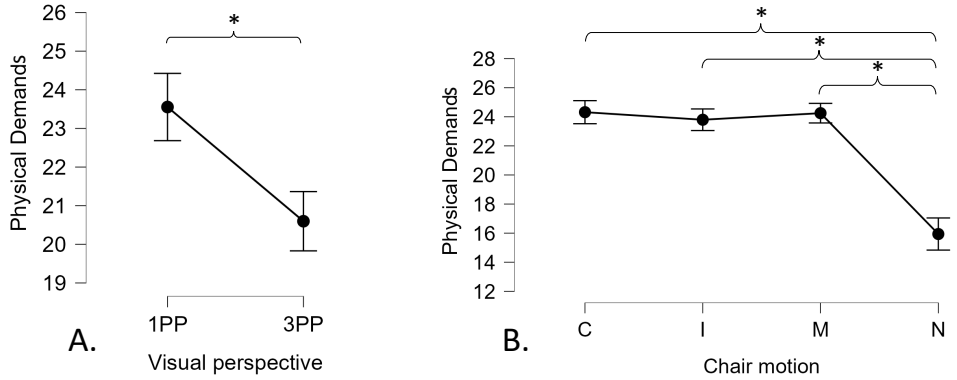

Figure 68: Effect of Visual perspective (A) and Chair motion (B) on participant's perceived physical demands. Error bars represent the standard errors (*p < .05). Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

Motion sickness

An effect of chair motion was found regarding participants' symptoms of motion sickness ($F_{1.701,61.229} = 12.377$, p< .001, η_p^2 = .256). Participants reported more symptoms when in motion than when the chair was static (Figure 69) (the Neutral chair condition was significantly different from all other chair motion conditions with p<.001).

Results regarding block type effect

There was no main effect of the Block Type factor, nor any interaction involving it in any of our analyses.

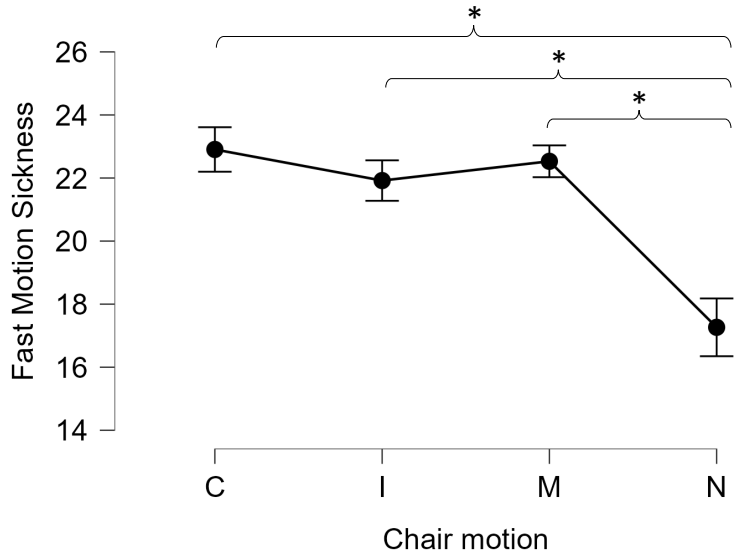

Figure 69: Effect of Chair motion on participants' motion sickness symptoms, measured using the FMS questionnaire (Keshavarz and Hecht, 2011). Error bars represent the standard errors (* $p <$ .05). Chair motion: C = Compatible, I = Incompatible, M = Mixed, N = Neutral.

Results regarding participants' field dependence effect

There was no interaction effect between the RFT results covariate and the other factors in the study for any of our measures. Note that we also grouped the RFT results into two categories based on the median (categorical measures) and tested them as a *between-subject factor* in our ANOVA, finding no effect of the RFT either.

16.4 | Discussion

This study aimed to analyze the effect of an operator's body motion on teleoperation performance and user experience. Specifically, as observed in Exp Ib, it also evaluated the manifestation of spatial (in)compatibility effects between the direction of the operator's body and the robot's tilt and motion. Additionally, the study investigated whether different types of visualization interfaces could mitigate the observed negative effects. To achieve this, 34 participants completed a teleoperation task in virtual reality. They were instructed to remotely control a spaceship and navigate through rectangle obstacles while precisely replicating their tilt under different viewing perspectives (1PP vs. 3PP). At the same time, their bodies were either stationary or in motion, in conditions spatially compatible or incompatible with the expected ship movement.

The main results revealed that, as expected, the operator's body movement affected teleoperation performance, particularly when the movement direction was spatially in-

compatible with the expected ship movement. The chair motion changed the control strategy, with operators starting to adjust the spaceship orientation earlier. Both mental and physical demands, as well as the level of motion sickness, increased when the operator was in motion. Regardless of the movement condition (compatible, incompatible, or static), operators performed better and preferred to teleoperate from a 3PP. Finally, under compatible movement and using a 1PP, participants tended to commit undershooting errors (compared to overshooting errors in 3PP) and showed a smaller range of movement. Additionally, our results do not show an effect of block type, indicating that participants did not seem to adapt to or anticipate the compatible and incompatible motions when they were in blocks consisting solely of trials with a similar chair movement condition. Moreover, our results do not reveal a significant effect of perceptual style on teleoperation performance. Throughout the task, the effects were consistent regardless of perceptual style. It is possible that participants adapted over time, with their perceptual style evolving during the task, which may have smoothed out performance differences. Indeed, as shown by Maneuvrier et al. (2021), these profiles are more flexible than one might think. The study indicates that subjects who initially reported high levels of cybersickness and low levels of presence in VR tended to shift their dependency profile towards a more independent level. The authors attribute this to adaptation and sensory recalibration aimed at reducing intersensory conflict, thereby minimizing negative effects in virtual reality.

Effect of motion and spatial (in)compatibility on teleoperation performance While no significant difference was found between the Neutral and Compatible conditions, our results indicate a significant drop in accuracy when motion was present, particularly in the Mixed and Incompatible motion conditions. The analysis of the Block Type effect (Mixed vs. Non-Mixed) also revealed no notable differences between the Compatible and Incompatible conditions. Thus, the observed differences between the Mixed and Neutral conditions likely reflect the influence of the Incompatible movement condition alone. These findings are consistent with spatial compatibility phenomena observed in the literature, which show that a stimulus or distractor that is spatially incompatible with the manual response can impact performance during visuomotor tasks (Simon and Craft, 1970; Simon et al., 1970; Stroop, 1935; Wallace, 1972), see Section 10.

Additionally, analyses of movement timing show that in the presence of chair motion, participants began controlling the spaceship earlier compared to the static condition. The times to reach 10% and 50% of the target angle were about 0.04 s earlier in the presence of movement (Figures 65 and 66). These findings align with previous research (Cowings, 1999; McDowell et al., 2005; Metcalfe et al., 2008; Salmon et al., 2011), which demonstrated that motion induced by vehicle simulators can reduce operators' movement speed and accuracy while increasing task completion time during visuomotor tasks, such as when manually reaching a touch screen in vehicle battle management systems (Section 9). The slowing of movement has also been observed in other altered force fields, such as microgravity

(Mechtcheriakov et al., 2002; Weber et al., 2016). In these studies, participants exhibited slower manual movements during tasks requiring rapid and accurate pointing toward a target. This slowing is often employed to ensure maximum precision in pointing tasks. It reflects an adaptation of CNS known as the speed-accuracy tradeoff (SAT), which suggests that the final precision of a response varies with the time taken to execute it (introduced by Woodworth (1899), and reviewed in Heitz (2014)). In our study, participants needed to perform a movement within a given timeframe, and starting the movement earlier could have been a strategy to save time. This adaptation likely helped participants maintain good accuracy in compatible movement conditions but proved only partially effective when the body's movement was in the opposite direction to the ship's movement.

Adapting to such disturbed gravito-inertial force fields takes time. For instance, Lackner and Dizio (1994) found that approximately 20 movement repetitions were needed to adapt to Coriolis forces and restore initial accuracy. It would be valuable to explore whether movement timing strategies evolve within our data, both in the initial blocks for rapid adaptation and across different blocks for slower adaptation.

Effect of motion on operator experience (mental, physical demands, and motion sickness) Consistent with our hypothesis, motion decreased the teleoperator user experience. Participants reported higher mental and physical demands and more symptoms of motion sickness during movement conditions. These findings align with Salmon et al. (2011), in which increased mental workload was observed under significant movement conditions, reflected in overall TLX scores and across all six subscales, including mental and physical demands scores. Additionally, our findings are in agreement with Bock (1998), which suggested that disturbed gravito-inertial force fields cause a sensorimotor discordance, requiring adaptation of motor programs to the new context and increasing mental resource demands. As noted by Salmon et al. (2011), the mental resources allocated to the tasks are likely to increase in a moving vehicle, potentially affecting performance on other tasks the operator must complete during such missions.

Furthermore, chair motion and the resulting intersensory conflicts led to increased motion sickness, although the average scores remained relatively low. This finding is consistent with research indicating that intersensory conflicts related to motion perception can induce symptoms of motion sickness (Bertolini and Straumann, 2016), as well as studies that have observed similar symptoms during screen-based tasks in moving vehicles (Cowings, 1999; Iskander et al., 2019; McDowell et al., 2007; McGill et al., 2017, 2020). Interestingly, even in the absence of movement, the mean questionnaire scores were not zero but around 16%, which could be attributed to virtual reality effects or residual motion sickness symptoms from prior movement blocks. In our study, primarily for ethical reasons, we took measures to reduce participants' motion sickness. As explained in Section 15, this involved setting up a teleoperation framework and accounting for head movements in the virtual environment. However, it's important to note that if an operator uses an HMD for

the operation, the teleoperation systems may not have been designed with features to mitigate motion sickness in dynamic environments. Further research is needed to address the effects of motion sickness in such scenarios.

Notably, although a spatial (in)compatibility effect was observed regarding participants' accuracy, it does not seem to significantly affect operators' experience in terms of physical or mental demands, nor their symptoms of motion sickness during a teleoperation task.

Effect of visual perspective on teleoperation performances and operator experience As expected, our results show better performance in 3PP compared to 1PP visualization. Indeed, participants made more absolute errors in 1PP (the difference is only 0.5 degrees but remains significant) and accomplished more overshooting in the opposite direction of the required tilt direction during the initiation of the spaceship tilt control. Additionally, they reported experiencing less mental and physical workload in 3PP than in 1PP. These results are consistent with previous studies that also demonstrated that 3PP is better suited for navigation and dynamic tasks (Bhandari and O'Neill, 2020; Temma et al., 2019; **?**; **?**), and enhances spatial awareness between oneself and surrounding elements. For example, the 3PP provides better space awareness (Gorisse et al., 2017), a more accurate estimation of distance to a target (Covaci et al., 2015), and an easier overall perception of distance (Ueyama and Harada, 2022). Therefore, these results also validate the decision made by researchers to propose third-person perspective (3PP) as a means of improving teleoperation interfaces (Erat et al., 2018; Kelly et al., 2011; Saakes et al., 2013; Saitoh et al., 2006; Temma et al., 2019; Thomason et al., 2017). Our results suggest that for a navigation task like ours, which requires perceiving the ship's orientation to avoid obstacles, the 3PP provides the best performance. This remains true regardless of the operator's motion conditions in the environment. Consequently, 3PP effectively mitigates the negative impacts of the operator's body motion.

Notably, the type of movement seems to influence the operator's behavior depending on the visual perspective used. Indeed, our results reveal an interaction between visual perspective and chair movement regarding the type of error made by the operators. When the direction of movement is compatible with that of the spaceship, operators in 1PP mainly commit undershooting errors, whereas in 3PP, they tend to make overshooting errors. These results are surprising. One possible explanation is the following: studies show that in 1PP, users feel a greater sense of embodiment (Galvan Debarba et al., 2017; Medeiros et al., 2018), while feeling less safe (Debarba et al., 2015). Additionally, spatially compatible chair motion might have been perceived as sensory redundancy, providing redundant visual and vestibular information about tilt direction, thus reducing intersensory conflict and potentially increasing the sense of embodiment. Indeed, it is well established that multisensory feedback, particularly vestibular and proprioceptive feedback, reinforces the sense of embodiment and presence in virtual reality when the environment is in motion (Leonardis et al., 2014). Consequently, it is possible that our participants were more cautious, making

more restrained tilting movements out of fear of overshooting. Furthermore, our results also show that in the condition where the subject was in 1PP and the direction of movement was compatible with that of the robot, their quantity of movement was decreased. This could be explained by the observed undershooting in these conditions; indeed, when orienting the spaceship, they always start from the same position (the horizontal position of the ship) to reach the target angle. If participants tend to undershoot, it means they were "covering less angular distance" in this condition compared to the others, which could be reflected in the measurements of the amount of movement performed.

HIGHLIGHTS

1. In conclusion, this main study highlights the detrimental impact of the operator's body motion on its teleoperation performance, particularly when the body motion direction is incompatible with that of the controlled robot.
2. Additionally, when in motion, participants tend to adopt a different control strategy, starting to adjust the robot's orientation earlier as if to allow themselves more time to make adjustments.
3. The subjective experience is also affected by chair motion, with participants reporting increased mental and physical workload and more severe symptoms of motion sickness, regardless of the type of motion.
4. Furthermore, in our teleoperation task — requiring solid perception and precise control of the robot's orientation to avoid obstacles — the 3PP proved to be the most suitable visualization interface, both in terms of performance and subjective experience, whether the environment is static or dynamic.
5. Unexpected results were observed when the operator was in the compatible motion condition and using a 1PP view. In this case, they tended to make undershooting errors and limit their movements, which we attribute to a possible heightened sense of embodiment, causing them to move more cautiously.

17 | Chapter conclusion

This second experimental block analyzed the effect of an operator's body motion on teleoperation performance during navigation and user experience. Results were compared to when the operator's body remained static and, similar to the first experimental block, it also evaluated the manifestation of spatial (in)compatibility effects between the direction of the operator's body and the robot's tilt and motion. Additionally, this block investigated whether different types of robot visualization interfaces could mitigate the observed negative effects. Therefore, within this block, 3 questions were addressed:

1. Does the operator's body motion impact teleoperation compared to a static condition?
2. Does spatial incompatibility between the motion directions of the operator's body and that of the controlled robot further impact teleoperation?
3. Does the type of visualization interface reduce or compensate for the negative effects related to the operator's body motions?

The results revealed that, as expected, the operator's body motion significantly affected teleoperation performance and subjective experience. Incompatible body motion directions led to a decline in performance, characterized by increased absolute errors. Both compatible and incompatible motion directions heightened participants' mental and physical demands, as well as their symptoms of motion sickness. Notably, when participants were in motion, they exhibited different robot control behaviors; specifically, they tended to start controlling the drone earlier when given a limited time to orient the robot to a target angle.

During our investigation into the suitability of different robot visualization interfaces for these environments, we tested various perspectives (first-person and third-person) and two types of horizon displays (fixed-wing and fixed-horizon). However, following our pilot study, we decided to focus exclusively on the effects of different perspectives. While we cannot conclusively state that this visualization compensates for the negative effects related to the teleoperator's motions, we found that the third-person perspective improves operator performance regardless of environmental conditions, thereby reducing the negative effects observed even in the presence of motion.

The next chapter will delve even deeper into our research questions and explore the transfer of the effects observed in the laboratory to real-world settings. Various types of experimental protocols will be proposed and tested to address these questions.

V. Ecological validity in teleoperation studies

The studies presented in this manuscript allowed, for the first time in a laboratory setting, to demonstrate that an operator's body motion can impact teleoperation performance and experience, particularly when the body's motion direction is opposite to the movement they wish to impose on the robot. We observed a decrease in performance both in tasks requiring trial-by-trial control of a static robot and in a navigation task requiring continuous control of the robot's orientation. Furthermore, our findings reveal that, for a navigation task, a third-person perspective visualization is more suitable, regardless of the teleoperation motion.

Yet, a fundamental question remains: *Do these effects transfer into real-world settings?* As explained in the Section 11, conducting laboratory experiments is crucial to ensure scientific rigor. Nevertheless, real-world situations are often far more complex and varied, which can result in differences between the effects observed in the laboratory and those found in the field. Several dimensions can be enhanced to better reflect real-world conditions and thus improve the ecological validity of a study. These include the task itself (stimuli and responses), the work environment, and the selection of participants based on the target population (Hoc, 2001; Schmuckler, 2001).

In this final chapter, we propose several approaches to studying the impact of dynamic environments and modified force fields on teleoperation in more ecological contexts. Experiments III and IV will be more representative of teleoperation environments, while Experiment V will be more representative of the teleoperation task and the target population. The research questions are as follows:

1. Does the supine position impact teleoperation, and how is it affected by an isolated and confined environment over time? Does the type of visual perspective (1PP vs. 3PP) reduce or compensate for the negative effects of the supine position and confined environment? (Exp III)

2. Do load factors induced by aircraft turns impact teleoperation? Does spatial incompatibility between the directions of the aircraft's turn and that of the controlled robot further impact teleoperation? Does the type of interface visualization reduce or compensate for the negative effects related to the operator's body movements? (Exp IV)

3. Does the supine position impact the teleoperation of a real drone from a first-person perspective during an inspection task? (Exp V)

18 | Analog missions

When operators are on missions, such as astronauts in space, or military personnel in crisis zones, they are in very unique contexts. They often are isolated in small teams at operational bases, in extreme environments that frequently pose a constant risk to them or their team. Terrestrial space analogs provide excellent controlled environments to study the effects of these specific and extreme work conditions. For example, analog missions such as MARS 105, Mars 520, SIRIUS, NEEMO, and the ANTARCTICA missions have revealed a variety of effects related to these space analog environments, including fatigue, cognitive impairments, mood alterations, social tension, sleep disorders, depression, changes in heart activity, immune system function, gastrointestinal problems, and more (see the review on the effects of isolation and confinement; Pagel and Choukèr (2016)).

Studying how modified force fields influence operators in space analog environments is useful for understanding how isolated and confined environments, more representative of real-life settings, could affect teleoperation differently. To achieve this, we adapted the protocol from Experiment IIb to conduct longitudinal studies during analog space missions (Section 11).

The Mars Desert Research Station (MDRS)



Figure 70: The Mars Desert Research Station, MarsClub, ISAE-SUPAERO, 2024

Our study was adapted to be conducted at the Mars Desert Research Station (MDRS) (Figure 70), located in Utah. This research station is owned and operated by the Mars Society, a nonprofit organization that promotes the exploration and human colonization of Mars. The station consists of six modules and includes a two-story habitat with a 6-meter diameter (the ground floor houses an EVA preparation room with a spacesuit simulator,

and the first floor is dedicated to living quarters), two observatories, a conventional and aquaponic culture laboratory, a functional microbiology and geology laboratory, and a repair and maintenance module. Due to its location in the Utah desert, this station provides immersion in an environment resembling the Martian landscape. This desert is a true geological analog, allowing for rigorous field studies similar to Martian geological missions. The organized missions last between 2 and 4 weeks, and the crew has only 2 hours of daily communication to send their reports to the base. As a result, the isolation and confinement of the crew in these modules facilitate relevant research on human factors. The crews may consist of scientists, engineers, and students of various education levels. During the analog mission, each crew member has a specific role: there may be a commander, astronomers, geologists, journalists, safety and health officers, systems engineers, botanists, and so on. Similar to a space mission, each person has a specific function. In addition to their daily tasks to ensure the smooth operation of the station, they conduct scientific experiments, often focused on equipment testing or evaluating the effects of space analog environments on humans.

The crew that conducted our experiment consisted of 7 ISAE-SUPAERO students (4 women and 3 men), and the mission lasted 4 weeks. The crew's daily mission reports are available on their ISAE-SUPAERO ClubMars website.

Research in analog missions: logistical and methodological constraints

The conduction of human factor experiments in analogous missions presents several logistical and methodological challenges that have to be carefully addressed to ensure the validity and feasibility of the research.

Space and resource constraints Space and resource constraints often limit the available equipment. Therefore, the used experimental material must either be already present on board the station or, if it needs to be brought, it must be transportable in a suitcase.

Time constraints The experiment must be designed or adapted to be short enough not to interfere with the crew members' daily schedules.

Communication and internet access constraints It is necessary to design or adapt experiments to be carried out autonomously by the crew members. Indeed, the crew has access to the Internet only two hours a day. Therefore, the experimental protocol must be explained extremely clearly so that they do not need to contact us or do research in case of problems or questions. Instructions must also include potential issues that could arise during the experiment or data collection, whether related to software or hardware and provide solutions for each of these issues. To ensure a good understanding of the protocol, the crew is often

briefed before departure, either remotely or in person at the laboratory, to explain directly how to conduct the experiment.

Adaptation of our experimental protocol

We adapted Experiment IIb to jointly study the effects of modified force fields and the spatial analog environment, as well as robot visualization perspectives, on virtual teleoperation performance. Therefore, the adapted experimental protocol aimed to answer the following research questions:

1. Does the supine position impact teleoperation, and how is it affected by an isolated and confined environment over time?
2. Does the type of visual perspective (1PP vs. 3PP) reduce or compensate for the negative effects of the supine position and confined environment?

Longitudinal study To account for the effect of time spent in the analog environment, measurements were repeated multiple times. To avoid overburdening their schedule, we asked the crew members to conduct our experiment once a week.

Experimental material We aimed to have participants perform a virtual teleoperation task in an environment where gravitational and inertial forces are altered. We asked the crew members to complete the teleoperation task while lying on their backs. In Unity, the task was modified to be performed in both bodily positions sequentially, allowing participants time to change positions. For each position, participants alternated between the two visualization perspective conditions, with the order counterbalanced automatically between participants and sessions.

Interface An interesting way to conduct our task would have been to immerse participants in the virtual environment using a headset (HMD) and control the spacecraft with a gamepad. However, when setting up this study, we did not have access to this equipment nor the time to purchase it. Therefore, we asked participants to perform the task on a computer and use the keyboard to control the spacecraft's tilt. The initiation of the spacecraft motion was performed by pressing the $\uparrow$ key once, and the adjustment of the spacecraft's tilt using the $\leftarrow$ and $\rightarrow$ keys on the keyboard.

Setup To perform the task in a seated position, participants only needed a desk and a chair. However, to position the computer in front of the participants while they were lying supine, we had to find a way to suspend and stabilize the computer using the available equipment. Therefore, to prepare the setup for the lying supine position, participants were asked first to place a mattress on the floor. Then, to position two chairs on either side of the

mattress and to lay out two broom handles across the seats of the chairs. The computer was placed between the two chairs, resting on the broom handles, with one handle positioned at the intersection of the screen and keyboard, and the other above the screen to prevent it from tipping. Finally, participants were instructed to place a small cushion under their right arm for support (Figure 71).



Figure 71: Supine lying position instruction - MDRS

Instruction manual A detailed Instruction manual was drafted, outlining the step-by-step experiment procedure, from setting up the experimental equipment for the seated and lying positions to conducting the task and finally to data collection and storage. The manual also anticipated potential difficulties participants might encounter and the following procedures.

To minimize order effects, the initial positions of participants were counterbalanced both between participants and across sessions. To achieve this, each participant was assigned an anonymous identification number. To determine the initial position for each session, participants had to consult the table below. The table provides guidance based on their participant number, indicating the starting position for each session. For example, participant number 1, in their first session (SESSION 1), had to begin the task in the Lying (L) position, followed by the Seated (S) position, as indicated in the LS cell. In session 2 (SESSION 2), they had to start in the Seated (S) position, followed by the Lying (L) position, as specified in the corresponding SL cell (Figure 72).

Participant n°	SESSION 1	SESSION 2	SESSION 3	SESSION 4
1	LS	SL	LS	SL
2	SL	LS	SL	LS
3	LS	SL	LS	SL
4	SL	LS	SL	LS
5	LS	SL	LS	SL
6	SL	LS	SL	LS
7	LS	SL	LS	SL

Figure 72: Table indicating the starting position for each session - MDRS

It was also necessary to ask participants to retrieve the session data at the end of each session and place it in the appropriate folders to create a backup in case errors occurred, and data was deleted. Additionally, they had to complete an Excel file, noting the order of the body positions performed (LS or SL) to ensure they had not mistakenly performed them in reverse order. Furthermore, if any difficulties were encountered or comments needed to be made regarding the session, they were asked to note them in the "Comments" section of the table (Figure 73). These comments are crucial for providing accurate feedback on the progress of each session, helping us explain any unusual results during data analysis, and ensuring data quality.

Participant number	Date	Time	Session n°	Body position order for the TILT experiment	Comments... *(everything went well?)*

Figure 73: Excel to be completed after each session

18.1 | Acquisition phase

This experiment was carried out by 7 crew members (**Crew 293**) at the Mars Desert Research Station (MDRS) for 4 weeks (Figure 74). Unfortunately, the collected data were unusable. Before analyzing the data, we reviewed the participants' end-of-session comments to assess how each session had unfolded. These comments revealed a lack of understanding of the importance of following the task instructions precisely as outlined in the instruction manual. Many participants took liberties during the experiments, compromising scientific



Figure 74: Photograph taken by the crew, extracted from the crew's logbook, showing the team conducting the experiment in the The Mars Desert Research Station, 2024.

rigor and engaging in behaviors that could bias the results, ultimately making them unusable. For instance, some participants missed sessions, others listened to music during the task, and a few had to interrupt the session after realizing they hadn't plugged in their computer. Some even exited the task prematurely and had to restart the entire experiment. Additionally, the protocol seemed suboptimal, as the majority of participants reported experiencing arm discomfort during the task. Given the small number of participants who completed the task correctly, the protocol-related issues (such as arm discomfort), and the lack of rigor in experiment execution, we concluded that analyzing the data would not yield meaningful results, as they would either be inconclusive or heavily biased by factors beyond our control.

These challenges highlight the difficulties associated with conducting experiments in remote or analog space environments, where researchers cannot be physically present. Possible causes could include insufficient preparation, lack of motivation and engagement, and communication or instruction issues. These challenges underscore the need for thorough participant training and preparation before starting the experiments. Furthermore, having a well-trained individual onsite to supervise the experiment—similar to how a researcher would operate in a lab—would have been essential to ensure the collection of reliable data. It should be noted that this crew was composed entirely of students, which is not the case for all analogous missions. In most major analog missions, there is a significant amount of support staff, and the participants are professionals.

HIGHLIGHTS

1. Analog environments serve as valuable laboratories for investigating the longitudinal effects of isolated and confined environments on phenomena we aim to study, such as in our case, the impact of modified force fields on teleoperation performance and the implementation of an adapted visualization interface for these environments.
2. However, conducting experiments remotely requires a different organization than conducting them in our laboratories, due to the constraints of space, time, and communication in these environments. It is essential to design short experiments, that require minimal equipment (preferably equipment already on site), and that are accompanied by an instruction manual prepared in advance by the researchers. This manual should clearly and concisely outline all the steps participants need to follow to carry out the task.
3. In this study, we proposed an experimental protocol adapted from one of our tasks to be conducted during a 4-week analog space mission at the Mars Desert Research Station (MDRS). Although data were collected, they were unfortunately unusable due to a lack of training before the missions and protocol errors. These difficulties highlight the challenges inherent in conducting experiments remotely.

19 | Virtual teleoperation under load factor

19.1 | Introduction

Experiment IIb illustrates the effects of operator motion and spatial motion incompatibilities on teleoperation. The findings reveal that movements generally influence both the behaviors of teleoperators—such as initiating robot control earlier—and their subjective experiences, including physical and mental demands as well as motion sickness. Additionally, spatially incompatible movements negatively affect the control accuracy of the robot. Furthermore, the experiment demonstrates that using a third-person visualization interface for the robot enhances both teleoperator's performance and experience.

The goal of the present study is to investigate whether these effects transfer in environmental contexts closer to the real working conditions of teleoperators (Section 11). To this end, our objective was to adapt the teleoperation task used in Exp IIb to be conducted within a teleoperation scenario corresponding to a military drone teleoperation case from a dynamic environment, which we present below.

Analysis of a teleoperation application case from a dynamic environment UAVs are transforming the way military operations are conducted. Although UAV teleoperation is typically performed from the ground, it may be advantageous for operators to manage these operations directly from an aircraft located in the same geographical area as the drone. In this context, a concept called Manned-Unmanned Teaming (MUM-T, Airbus (2022a)) aims to integrate UAVs with the next generation of manned military aircraft, enabling them to work together. This approach presents several advantages: it allows for better situational awareness, improves resistance against satellite data link jamming, and allows easier relative flight (notably during the drone drop phase and formation flying for airspace management or electromagnetic and visual stealth). This approach is central to developing the Future Combat Air System (FCAS). The Next Generation Fighter (NGF), set to replace the French Rafale by 2040, is expected to be supported by so-called "Remote Carriers" (see Figure 75); hybrid drone-missile systems that will carry out environmental reconnaissance missions and operate within a combat cloud. The interaction between the operator on board an aircraft and the unmanned systems remains an open question. NATO has defined 5 levels of interoperability (LOI) commonly used in the field (AKSIT, 2012):

- LOI 1: Indirect receipt of UAV sensor data
- LOI 2: Direct receipt of UAV sensor data
- LOI 3: Control/monitoring of the UAV payload
- LOI 4: Control/monitoring of the UAV flight
- LOI 5: Control/monitoring of UAV launch and recovery

Each level represents an advancement over the previous one.



Figure 75: Projection of the Future Combat Aircraft Systeme (FCAS) by remote carries. FCAS is a common project of France, Germany and other European nations. (Airbus, 2024a)

Operational tests are being conducted by industrial and military entities around the world. Their results are rarely published, but instead shared through press releases and promotional videos, except for in-depth studies carried out by the German Aerospace Center (Andreas E. Voigt, 2019; T Mehling, 2019; Tobias Paul, 2013). Analyzing various videos, including those from Airbus and its partners, highlights the practical applications of MUM-T. For instance, Airbus' demonstration of MUM-T involving helicopters at LOI 4 (Airbus, 2022b) provides a concrete example of this technology in action. A screenshot from the video presented in Figure 76 shows a typical teleoperation scenario from a moving vehicle: two agents on board a helicopter, with the pilot on the right and an operator on the left monitoring or piloting a UAV using a screen-type interface positioned just above the aircraft's cockpit.

When on board a flying vehicle, passengers and, consequently, the UAV operator may be exposed to gravitational-inertial changes induced by the vehicle's movements (Section 6). For instance, passengers can experience significant differences in load factor during aircraft turns. In straight and level flight, the load factor is one, meaning only the body's weight is felt. However, when an aircraft turns or changes altitude, the load factor increases, resulting in a sensation of greater weight. For instance, at 2g, a force equivalent to twice the body weight is experienced. This principle also applies to helicopters. As a reference, the Rafale, a French fighter jet, has a positive load factor limit of 9g, while smaller aircraft typically have a limit of around 4g. Literature shows that load factors below 3g can impact human sensorimotor and cognitive performance. For example, hypergravity induced by a centrifuge can affect manual control and the perception of body orientation



Figure 76: First LOI 5 demonstration for Airbus and Schiebel in 2018 (Airbus, 2018). The setup is similar to what we have imagined for our experiment (Figure 78). The mission commander on the left controls the drone using screens in front of him. The stick on his right hand seems to be the command for the drone (but we haven't been able to confirm that).

(Clark et al., 2015). During a task requiring the alignment of the body with the vertical while using a manual rotary controller in hypergravity (centrifuge), subjects overestimated the roll inclination of their body, leading to errors in manual control performance. Initial performance degraded by 26% at 1.5g and 45% at 2g. However, improvement was observed with exposure, bringing performance back to near-initial levels. Hypergravity has also been shown to affect force production when using an isometric joystick. One study found that force production was exaggerated mainly at the beginning of movement; the authors noted, "*these excesses of produced force are probably due to less appropriate central commands since it manifests before proprioception becomes effective*" (Girgenrath et al., 2005). Chomienne et al. (2021) showed that hypergravity induced in parabolic flights could also affect the neuromuscular control of whole-body movements, with a systematic underestimation of movements compared to the hypogravity condition. Finally, studies also indicated that cognitive processes seem impaired in hypergravity (Albery, 1989; Ercan and Gunduz, 2020; Levin et al., 2007). Hypergravity has been shown to hinder the memory encoding process, such as recognizing words that were previously encoded (Levin et al., 2007), and an older study reported high mental load in operators subjected to biodynamic stress factors such as noise and acceleration (induced by a centrifuge) (Albery, 1989). Additionally, on board an aircraft during symmetrical turns with low load factors, a disorienting effect known as the Coriolis effect may occur. During prolonged turns, after the sensation of rotation fades, the corresponding semicircular canals in the inner ear return to a resting state. If the pilot then

tilts their head forward or to the side, the centrifugal force shifts to another semicircular canal, causing a disorienting sensation of roll, yaw, or pitch deviation (Ciboulet, 2002).

To study the effects of dynamic environments on teleoperation in a more ecological setting, we decided in this study to examine the impact of load factors induced by a moving aircraft on the performance of participants performing a teleoperation task in a scenario similar to the one demonstrated for Airbus and the one from Schiebel in 2018 (Figure 76). For this purpose, the teleoperation protocol used in Experiment II.b was adapted to be conducted on board a Robin DR400 aircraft in flight, in level flight (1g), and during turns inducing load factors up to 2g. Seated next to the pilot, participants performed this teleoperation task using a tablet mounted above the cockpit and controlled a virtual robot via a Bluetooth controller. As in Exp IIb, we also investigated the effects of spatial compatibility between the direction of the aircraft turn and the robot's movement, as well as the effects of the robot visualization perspectives used (1PP and 3PP).

Our research questions where the following:

1. Do load factors induced by aircraft turns impact teleoperation?
2. Does spatial incompatibility between the directions of the aircraft's turn and that of the controlled robot further impact teleoperation?
3. Does the type of interface visualization reduce or compensate for the negative effects related to the operator's body movements?

Based on the results obtained in Exp IIb and the literature, we expected that load factors would impact teleoperation performance and that spatially incompatible motion directions would further exacerbate this impact. We anticipated that when the load factor exceeds 1g, participants would start to control the robot earlier and experience increased mental and physical loads as well as symptoms of motion sickness. Furthermore, we expected that using the 3PP would enhance both performance and subjective experience.

19.2 | Methods

Participants

A total of 14 healthy volunteers (6 females, 1 left-handed, mean age= 28,41, SD= 9.7), students and staff of the French Aerospace Engineering School ISAE-SUPAERO participated in the study. Participants had normal or corrected-to-normal vision, no history of neurological or psychiatric diseases, or severe motion sickness susceptibility (MSSQ-Short questionnaire; Golding (2006)), and were free of the regular use of medication. Six of them had no flying experience, and 8 were pilots (including 6 with moderate experience with 10-200 flight hours and 2 with solid experience: more than 1000 flight hours). Participants were in good health and had no history of vestibular disorder. They were asked to have little or no experience of motion sickness.

Ethic statement

All volunteers were informed of their rights and gave their written informed consent for participation in the study, according to the Declaration of Helsinki. This work was approved by the Research Ethics Committee of Toulouse (CER number 2024-881).

Experimental device

Aircraft The aircraft used to induce the load factor during the experiments was the ISAE-SUPAERO experimental four-seater airplane Robin DR400 (Figure 77).



Figure 77: ISAE-SUPAERO Robin DR400 used for the experiment

Teleoperation material Participants performed the teleoperation task using an 11-inch tablet as the computer screen interface and an Xbox Bluetooth gamepad as the controller. The tablet was mounted on the canopy above the cockpit, facing the participant. The gamepad was equipped with a strap that participants fastened around their knee to prevent it from falling in case of an emergency, following mandatory safety protocols to avoid distracting the pilot. Participants were also equipped with a headset (standard airplane equipment) and listened to air traffic control (TOULOUSE INFO 121.250) to immerse themselves in an operational environment. Additionally, they were asked to bring and wear a cap and sunglasses to protect themselves from light and glare.

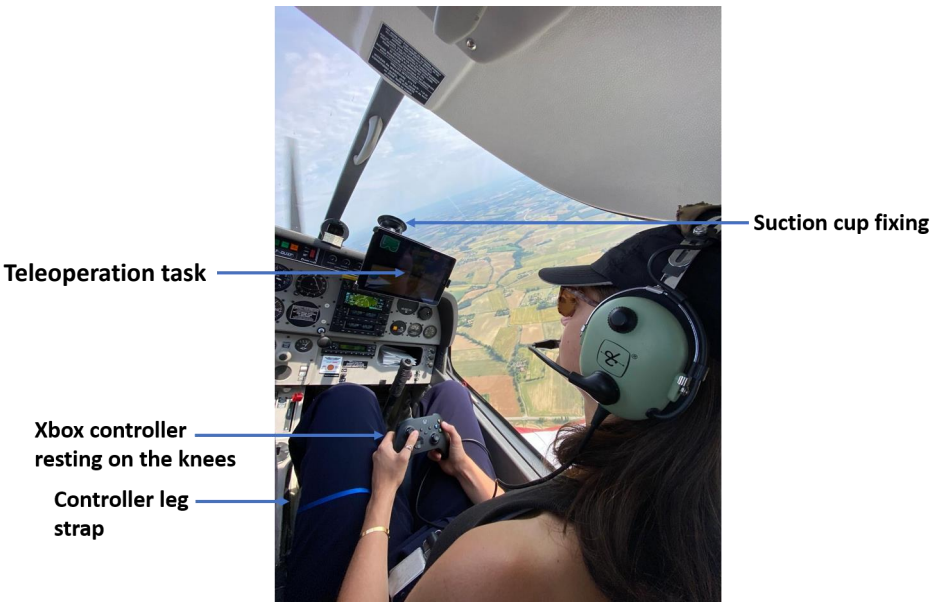

Figure 78: Experiment setup during design flight for the experiment.

Study design and procedure

Rod and Frame Test and Teleoperation task Both tasks were similar to the Exp IIb presented in Section 16, except that the Teleoperation task was performed on an 11-inch tablet as the computer screen interface and with an Xbox Bluetooth gamepad.

Load factor conditions The pilot was instructed to maintain a level flight with bank angles of 30°, 45°, and 60°. The objective was to induce load factors of 1.2g, 1.4g, and 2g, respectively. The actual load factors experienced by the participants were measured using the ILevil 3-10-AW system, which was installed inside the aircraft. This system measures, records, and displays flight information on a phone or tablet, such as the aircraft's speed, acceleration, attitude, altitude, and bank angles (Figure 79 for an example of data recorded by the ILevil for a participant).

We were thus able to verify whether the target angles were achieved and, consequently, whether the load factors were as well. Analysis of the ILevil data showed that the bank angles achieved by the pilot did not precisely match the target angles, and therefore the load factors were not exactly 1g, 1.2g, and 1.4g. On average, participants experienced load factors of 1.1g $\pm$0.1, 1.3g $\pm$0.1 and 1.9g $\pm$0.2 during the different experiments (Table 4).

Spatial Compatibility Conditions The aircraft could perform turns to the right and left. Therefore, participants could experience the task in four compatible conditions: the Neutral condition, in which the aircraft was in level flight; the Spatially Compatible condition, in which the aircraft's turn was in the **same direction** as the direction needed to clear the obstacle; and the Spatially Incompatible condition, in which the turn was in the **opposite**

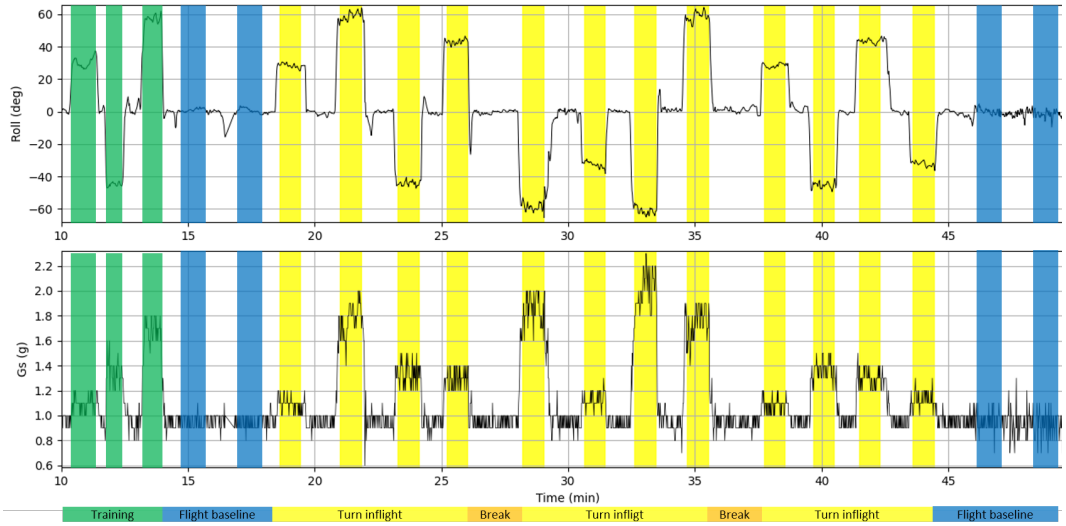

Figure 79: Flight parameters (roll and load factor) for an example participant.

Roll (ϕ)	$\phi_{exp} \pm$ sd	Load Factor (Gs)	$Gs_{exp} \pm$ sd
30°	30° ±2	1.2g	1.1g ±0.1
45°	44° ±2	1.4g	1.3g ±0.1
60°	59° ±3	2.0g	1.9g ±0.2

Table 4: Targeted roll and load factor compared to mean experimental data

direction. The spatial compatibility conditions were organized differently from those in Experiment IIb. In Exp IIb, each trial was categorized as compatible, incompatible, or mixed; the chair constantly moved according to the orientation of the obstacles to create the desired spatially compatible or incompatible conditions. In the aircraft, it was impossible to make a turn for each obstacle due to the limited space between obstacles. Therefore, we decided to perform one turn per trial, with a total of 15 obstacles. Thus, each trial featured situations where some obstacles were compatible, and others were incompatible with the aircraft's movements, which remained constant.

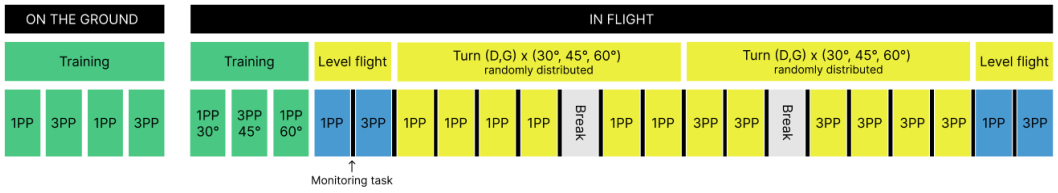

Figure 80: Experimental plan.

Procedure (Figure 80)

Ground Training Before the flight, participants performed ground training to familiarize themselves with the task, the perspectives, and the controllers. The training consisted of 4 trials (i.e. two in the 1PP and two in the 3PP).

In-Flight Training In the aircraft, participants began with a second training session designed to acclimatize them to perform the task under the different load factor conditions. Participants completed three trials: the first with a 30° bank angle, the second with a 45° bank angle, and the third with a 60° bank angle.

In-Flight Task Participants began with the level flight condition (1g), performing 2 trials for each perspective. Then, they proceeded to the task involving varying load factors. Participants completed 6 trials in the 1PP and 6 trials in the 3PP. During these trials, the pilot could execute turns to the right or left at 30°, 45°, or 60°. Each participant experienced all combinations of conditions, which were randomly assigned. They performed all conditions once except for the level flight conditions that they performed twice (one at the beginning and one at the end of the flight). In total, the training included 7 trials for acquisition and 16 trials for the main task. Between each trial, participants had a 60-second interval to complete a monitoring task typically performed by pilots. This task involved reading and comparing the magnetic heading with the directional heading, as well as identifying a landmark on the ground. The purpose of this monitoring task was to maintain situational awareness, although no performance metrics were collected during these phases of the flight.

Data processing and statistical analysis

This study investigated the relationship between load factor, spatial compatibility, visual perspective, and teleoperation performance. We evaluated participants' performance based on their absolute and signed error at each obstacle, and their time to reach 10%, and 50% of the obstacle tilt. Participants' user experience was assessed by their level of motion sickness and reported mental and physical demands.

Data were analyzed using a three-way repeated measures ANOVA with Load Factor (1g, 1.1g, 1.3g, 1.9g), Spatial Compatibility (Compatible, Incompatible, Neutral), and Visual Perspective (1PP, 3PP) as within-subject factors. Mauchly's test of sphericity was conducted, and when the assumption of sphericity was violated ($p < .05$), Greenhouse-Geisser corrections were applied to adjust the degrees of freedom. Post-hoc comparisons were performed using the Holm correction to control for multiple comparisons. All statistical analyses were conducted using JASP 0.18.3.

Covariates included in the analyses were the number of flight hours for each subject and the mean error on the Rod and Frame Test. Of the 14 subjects, one was identified as an outlier due to difficulty in understanding and performing the teleoperation task and was therefore excluded from the analyses.

19.3 | Results

No significant effects of Load Factor, Spatial Compatibility, or Visual Perspective were observed on any performance measures. Similarly, no effects of Spatial Compatibility or Visual Perspective were found on the participants' subjective experience. However, a significant effect of Load Factor was identified in terms of mental and physical demands, as well as on participants' reported symptoms of motion sickness, as described hereafter.

Mental demands An effect of the Load Factor was found regarding the participant's perceived mental demands ($F_{1.8,21.86} = 8.73$, $p < 0.001$, $\eta_p^2 = .34$). Participants' mental demands were perceived as higher when exposed to 1.9g compared to all other conditions (right graph of Figure 81).

Physical demands An effect of the Load Factor was found regarding the participant's perceived physical demands ($F_{1.43,18.60} = 16.3$, $p < 0.001$, $\eta_p^2 = .49$). Participants' physical demands were perceived as higher when exposed to 1.9g compared to all other conditions (left graph of Figure 81).

Motion sickness A significant effect of the Load Factor was found regarding participants' symptoms of motion sickness ($F_{1.46,16.06} = 5.11$, $p = 0.027$, $\eta_p^2 = .057$). Participants felt more motion sickness symptoms when exposed to 1.9g compared to all other conditions and when exposed to 1.3g in comparison with 1g (center graph of Figure 81).

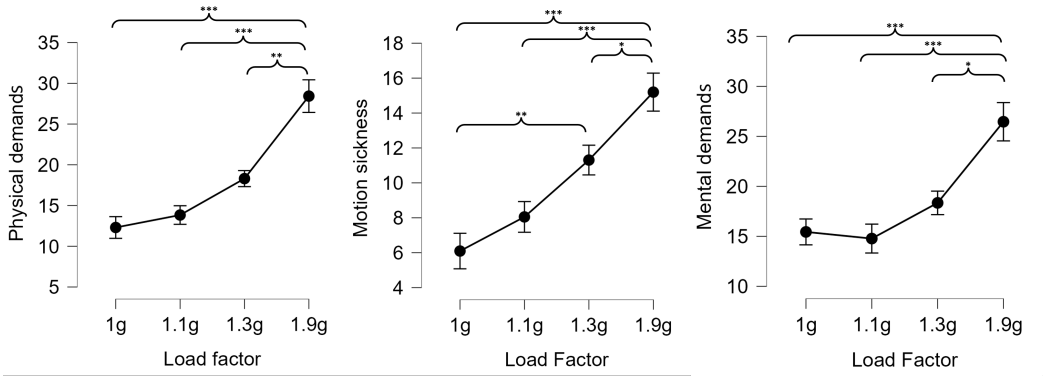

Figure 81: Effect of load factor on subjective mental and physical demands as well as motion sickness. Error bars represent the standard errors (*p < .05,**p<0.01,***p<0.01)

19.4 | Discussion

The objective of this study was to propose an experimental protocol that ecologically evaluates the impact of dynamic environments on teleoperation. Specifically, this protocol aimed to analyze the effects and possible interactions between spatial compatibility, visualization perspectives, and different load factors on the control performance of a remote robot during an obstacle avoidance task. To achieve this, the teleoperation protocol and task from Exp IIb were adapted to a new teleoperation scenario that more accurately represents the reality faced by teleoperators. Fourteen participants completed a simulated teleoperation task aboard a light aircraft in flight. The teleoperation interface consisted of a tablet located on the canopy, while the controller was a joystick placed on the participants' laps. Participants could view the robot either from a 1PP or a 3PP. The aircraft was either in level flight (1g) or performing turns at various bank angles to induce load factors ranging from 1.2 to 1.9g. The turns could be in the direction of the robot's movement or in the opposite direction, creating scenarios of spatially compatible or incompatible aircraft movement.

The results showed no significant effect of the load factor, no impact of spatial compatibility between the aircraft's movements and those of the robot, and no influence of visualization perspective on participants' teleoperation performance or teleoperator behaviors. Thus, contrary to what was expected, the dynamic environment and the associated load factors did not affect teleoperation performance, whatever visualization interface they used. Additionally, we found no effect of visual perspective or spatial compatibility on subjective experience, including perceptions of mental and physical workload and the level of motion sickness during the task. However, our results do show a significant effect of load factor on participants' subjective experience. Participants reported higher mental and physical demands and increased levels of motion sickness when exposed to a load factor close to 1.9g.

Effect of load factor and spatial compatibility on behavior and performance Contrary to our expectations, this study did not reveal any effects of load factor or spatial compatibility on behavior and performance. Several reasons could explain this outcome.

First, the teleoperation scenarios in Exp IIb and this study are fundamentally different. In Exp IIb, teleoperation was immersive through the use of an HMD, creating a complete visual-vestibular conflict, whereas in this study, the teleoperation interface consisted of a tablet placed above a cockpit. This scenario was not immersive; participants could see the external environment of the aircraft in their peripheral vision, allowing them to visually estimate the vehicle's movements, which may have reduced the intersensory conflict. In fact, in a study where experimenters tested different placements of a tablet inside a moving vehicle, they found that when the tablet's position allowed for peripheral vision of the vehicle's movements, it could decrease the visual-vestibular conflict (Kuiper et al., 2018). Hence, the reduction in intersensory conflict could explain why teleoperation was less af-

fected in this non-immersive scenario under a high load factor.

Furthermore, in the present study, during coordinated turns, the participants' head and body axes were always aligned with the resultant gravito-inertial force vector, corresponding to the vectorial sum of Earth's gravity and the centrifugal forces induced by the turn. As a result, the otolithic organs and the somatosensory system did not detect any roll tilt and consistently signaled an upright position. Thus, only the intensity of perceived gravity changed, while its perceived orientation remained upright and constant. It is possible that a difference in gravity intensity, such as this one, affects teleoperation less than a difference in gravity orientation. Further research would be necessary to address these questions.

Additionally, the task began when the aircraft was stabilized in a turn at the target angle. While the aircraft was tilted, there were no variations in roll axis movement during the task. As a result, the body may have been perceived as stable along the roll axis by the vestibular and somatosensory systems. Therefore, it is not surprising that we did not observe an effect of spatial compatibility between the robot's roll movement directions and those of the aircraft in this experiment. This makes it challenging to study the effect of spatial compatibility when evaluating the load factor. For future studies examining the effects of spatial compatibility between the movements of a vehicle and those of a robot using this teleoperation task, it would be beneficial to ensure that the vehicle induces actual lateral tilt movements to the right and left while advancing.

Effect of robot visualization perspective It might be the case that, as gravity was perceived by the otoliths as aligned with the participant's longitudinal axis, there was no real perception of body tilt. It is possible that this type of conflict focused on gravity intensity rather than its orientation, has less impact on a task involving the perception of the robot's tilt in the 1PP. Therefore, 3PP might not be as necessary as anticipated in this context.

Effect of load factor on mental and physical demands Between 1g and 2g, in this experiment physical and mental demands were multiplied by 2.6 and 1.7, respectively. This is consistent with theories suggesting that a change in force fields induces a sensorimotor mismatch that requires adaptation of motor programs to the new context and demands more mental resources (Bock, 1998). However, during our experiment, performance remained intact. Bock explains that the results of experiments conducted in modified force fields can vary depending on the tasks the subjects need to perform (Bock, 1998). Indeed, experimental tasks can have different difficulty levels and, consequently, require more or fewer mental resources. In our case, it is possible that a sensorimotor mismatch occurred and was perceived by the participants (as indicated by the subjective results). However, since our task was relatively simple, it may have allowed for effective adaptation, which could have prevented any performance degradation.

Effect of load factor on motion sickness Consistent with our expectations, even though our participants were not initially particularly sensitive to motion sickness (as measured by the MSSQ-Short questionnaire), motion sickness increased during exposure to 2g compared to level flight (1g), with an average increase of 2.5 times. Few studies address motion sickness when visuo-vestibular conflict occurs under hypergravity conditions. However, many studies discuss motion sickness when subjects move their heads on a centrifuge (Newman et al., 2013; Young et al., 2001), creating a Coriolis effect. Although our participants were instructed not to move their heads, we did not secure their heads during the experiment, so it is possible that some movements occurred, inducing a slight Coriolis effect that could contribute to motion sickness alongside the intersensory conflict between visual and vestibular information possibly induced by the interface visualization (Bertolini and Straumann, 2016; Iskander et al., 2019).

Literature also shows that adaptation to motion sickness induced by the Coriolis effect can be achieved by exposure to these effects through head movements in a centrifuge. For example, in one study (Newman et al., 2013), after five daily training sessions, motion sickness symptoms were reduced by more than half compared to the first day, and 17 days after the training, the scores remained stable. However, this adaptation to head movements must be performed in all planes of space, as training in one plane, such as the roll plane, does not transfer to other planes, such as the pitch plane (Garrick-Bethell et al., 2008).

Recommendations Given the results and discussion of this study, we would like to express some recommendations for scenarios of this type: First, the operators' heads should be aligned with the load factor to avoid a strong Coriolis effect. We observed that individuals tend to keep their heads naturally aligned. However, even with the head naturally aligned, we noted increased motion sickness symptoms. Therefore, it would be ideal to find a way to stabilize the operators' heads.

In line with this, interfaces should be positioned at the level of the subject's head, and operators should use controllers that do not require them to look at them during the vehicle's movement. Indeed, if the operator tilts their head, they will also experience the Coriolis effect.

Additionally, we recommend using controls that allow the arms to rest on support and use touchscreen interface with caution, for instance. This way, the pilot will not have to support their arm under increased load factor.

Finally, on aircraft with low load factors (e.g., a radar plane) that generally do not perform 60° turns, training for MUM-T operators under a load factor of more than 2g may be beneficial. This way, if the aircraft performs an unusual maneuver, the operators will be prepared to handle it. However, on aircraft that may expose passengers to load factors exceeding 2g, it would be advisable, in addition to training, to select operators with low susceptibility to motion sickness and train them accordingly.

Limitations The present study has some limitations that should be considered when interpreting the results. A primary limitation is that our study group was relatively small compared with experiments conducted in laboratory conditions, with only 13 subjects providing usable data.

All flights were conducted under relatively low turbulence conditions. The main difference between subjects was the presence of sun glare. During the 60° turns, which lasted about one minute, subjects repeatedly faced the sun. However, at times, a cloud layer would block the sun. Several participants reported that sun glare was a distraction.

Additionally, in this study, compensation for the transition between the 1PP and 3PP phases among participants was neglected; during the stages with a load factor greater than 1g, participants always performed the 1PP condition first and the 3PP condition second. However, an analysis of the results from the 1g trials, conducted at the beginning and end of the experiment, showed no significant difference between the 1PP and 3PP phase results.

HIGHLIGHTS

1. This study is among the first to examine the effects of load factors on teleoperation performance in the context of Manned-Unmanned Teaming (MUM-T), and it demonstrates the feasibility of using the ISAE SUPAERO DR400 aircraft for such experiments.
2. The first results reveal that, although load factors do not significantly affect teleoperation accuracy, they considerably impact subjective measures, including physical and mental demands, as well as motion sickness.
3. For MUM-T operations, we recommend aligning the operators' heads with the load factor to minimize the Coriolis effect, suggesting that coordinated turns are preferable. Displays should be positioned at head level to avoid additional strain and motion sickness. Control interfaces should allow operators to rest their arms, reducing physical tension under high loads. Additionally, given the challenges associated with high load factors, touchscreens should be used with caution in such environments.
4. Our work paves the way for more extensive investigations with larger samples and more varied flight conditions, which are necessary to fully understand and optimize operator performance in MUM-T scenarios. Furthermore, developing a robust protocol for these experiments will support ongoing advancements in the field, ultimately contributing to the safe and effective integration of MUM-T into military operations.

20 | Supine FPV teleoperation for inspection tasks

20.1 | Introduction

The previous studies presented in this chapter enhanced the ecological validity in terms of the working environment. This present experimental protocol goes further by improving the ecological validity of the teleoperation task itself (Section 11).

As explained in Section 2, many teleoperation tasks involve the inspection of infrastructure located in hazardous environments. For example, ensuring the crew's safety during space missions requires the spacecraft or habitat to remain in good condition. A critical safety measure is regularly inspecting the station's exterior to detect potential damage from meteorite impacts and orbital debris (Hyde et al., 2019). Traditionally, these inspections, such as those on the ISS, have been performed by astronauts during extravehicular activities (EVAs). However, EVAs expose astronauts to dangerous radiation and risks, and they are time-consuming and energy-intensive. To mitigate these risks, there is growing interest in using UAVs or drones for such tasks. This approach is becoming more feasible, with an increasing number of collaborative operations between astronauts and remotely operated robots (Fong et al., 2013). Recent advances in robotics have demonstrated the potential of using small satellites for inspection tasks (Henshaw et al., 2009; Nanjangud et al., 2018), potentially reducing the frequency of EVAs and the associated risks to astronauts. On Earth, drones have already proven their efficiency in inspecting structures such as bridges and wind turbines, offering both precision and reliability (Seo et al., 2018; Shihavuddin et al., 2019).

Therefore, to better simulate the real-world conditions of a teleoperation task, we were inspired by Weiss et al. (2022) study to design a new experimental protocol conducted in the ISAE-SUPAERO aviary. Participants controlled a real drone (DJI FPV Combo – First-Person View Drone) to perform an infrastructure inspection, similar to a space station. This approach ensured that the teleoperation objective, stimuli, and participants' responses were more closely aligned with the real-world tasks and challenges faced by teleoperators.

In a dynamic environment, teleoperators can become misaligned with the vertical axis, and when using a Head-Mounted Display (HMD) for visualization, intersensory conflicts may arise between graviceptive cues and perceived motion from the visual, vestibular, and somatosensory systems (Section 6). Furthermore, as highlighted in Section 8, research suggests that both body tilt and intersensory conflicts can impair the visuomotor skills essential for effective teleoperation. But how do these effects translate to the control of a real drone?

To answer this research question, the present study investigates the impact of the visuo-vestibular conflict induced by the supine position on user performance and experience during a visual inspection task and an instruction execution task. We designed an experimental setup using a space station mock-up and a drone piloted in First Person View (FPV).

Participants performed the tasks twice, once in a standing position and once in a supine position. We expected decreased performance in the supine position, which would manifest as fewer detected anomalies, less efficient trajectories, and errors in the execution of directional instructions. Furthermore, we anticipated a deterioration of user experience, with an increase in cybersickness symptoms and mental workload when performing the task in the supine position.

20.2 | Methods

Participants

14 healthy volunteers participated in the study (2 females, 2 left-handed, mean age = 27.64, SD= 5.5). Participants had normal or corrected-to-normal vision, no history of neurological, psychiatric diseases, or severe motion sickness, and were free of the regular use of medication. 5 out of 14 were experienced drone pilots, and the rest were novices.

Ethic statement

All volunteers were informed of their rights and gave their written informed consent for participation in the study, according to the Declaration of Helsinki. This work was approved by the Comité d'Éthique de la Recherche - CER at Université de Toulouse (CER number 2024-887).

Experimental device

Aviary The study was conducted in the aviary of the French Aerospace Engineering School ISAE-SUPAERO laboratory. The dimensions of the flying area are 8m$\times$8m$\times$3m. The aviary is equipped with the OptiTrack system that enables tracking drones' position when equipped with motion capture markers (small reflective balls).

Drone The quadcopter used for the experiment was the DJI FPV controlled with a head-mounted display and a two-hand remote controller connected in Bluetooth. The drone was equipped with 7 reflective balls distributed at unequal distances across its body to create a recognizable pattern. The OptiTrack system of the aviary tracked this pattern to provide the position and the rotation of the drone in space during the trials.

Space station mock-up Participants had to perform an inspection task around a space station mock-up, which consisted of three interconnected modules (ESA module, CNES module, and ISAE module) joined by a cubic node (Figure(82). The ESA and CNES modules were aligned horizontally, forming a right angle around the node, while the ISAE module was vertically positioned above the node. The ESA and CNES modules were the largest, each with an 80 cm diameter and a length of 120 cm. The ISAE module, oriented towards

the aviary's ceiling, had the same diameter but was shorter, measuring 60 cm long. The exterior of the cylinder was covered in custom-printed neoprene to replicate the texture of futuristic space station modules, featuring elements like panels, grids, and convector heaters. To create a realistic environment, partners' logos (ESA, CNES, and ISAE-SUPAERO) were applied to the module's surface. To facilitate the localization of the anomalies during the visual inspection task, codes were printed on the module's visible panel. A code was composed of one letter and one number (Figure 82). Each half of the cylinder had letters, and the panels were numbered from top to bottom. The station was placed on wood supports at around 80 cm above the floor. Additionally, three reflective markers were placed on the top of each cylinder, allowing the OptiTrack system to know the exact location of the mockup.

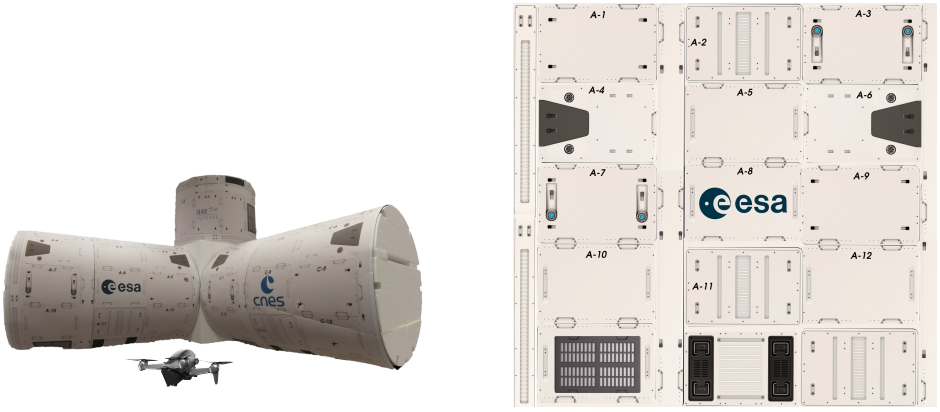

Figure 82: The mock-up of the space station with the DJI FPV drone on the left and an example of the ESA panel with printed codes consisting of a letter and a number on the right.

Study design and procedure

Inspection task For the visual inspection task, the participants had 5 minutes to fly over the space station mock-up and detect and identify as many anomalies as possible. A total of 12 anomalies were randomly distributed on the station's panels, in different locations for each session. The participants were not aware of the number of anomalies. To locate an anomaly, users had first to take a photo by pressing a specific button on the remote control when they were in front of the anomaly, then to verbally indicate the code of the panel on which it was located, as well as its position on the panel (top or bottom, right or left, or center). They had also to indicate the size (large or small) and the type of anomaly. There were two types of anomalies: a circular impact of a meteorite and a delamination fracture (Figure 83). For example, a well-identified anomaly was: "*Big Impact at the top left of A2*".

Instruction execution task The instruction execution task consisted of executing a sequence of verbal instructions such as "Move Forward", "Move Backward", "Move Up" and

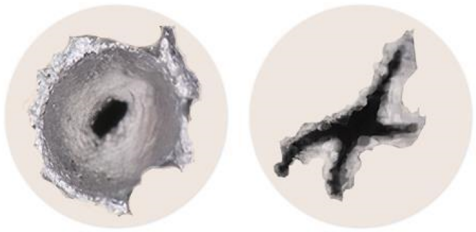

Figure 83: Type of anomaly: a circular impact on the left and delamination fracture on the right

"Move Down" or directions such as " Up", "Down", "In Front" and "Behind". A total of 76 instructions were recorded in an audio file. Each participant heard the same list of instructions.

Procedure Before the main experiment, participants completed two different training sessions. They first completed a visual training session in the entire aviary to familiarize themselves with the drone's controls and its sensitivity. This training session was followed by another session where they were equipped with the FPV headset. The participants flew around the mockup and were asked to find specific panels placed in the aviary to familiarize themselves with the station's design and the identification of the anomalies.

The experiment consisted of two tasks, a primary inspection task, and a secondary instruction execution task, that had to be performed in 2 body position conditions (standing upright and supine, Figure 84). Participants completed both tasks consecutively in one of the two body positions and then repeated them in the other position. The starting position order was systematically varied across participants to ensure a balanced distribution. After each body position condition, participants filled in a NASA Task Load Index (TLX) questionnaire to assess their perceived workload and were asked to assess their level of cybersickness.

Data processing and statistical analysis

For the inspection task, we evaluated participants' performance based on the number of detected anomalies, the number of identification errors, the speaking duration to identify anomalies, the efficiency of the trajectory (ratio between the number of detected anomalies and the distance traveled for the inspection), the average speed of travel, the distance to the station and the smoothness of movement.

In the instruction task, we evaluated the number of movement errors (for example, going forward instead of upward) in each body position. We also analyzed the number of errors for each type of word (verbs or directions) and for each axis (X or Z). Scores from the NASA-TLX questionnaire (Hart and Staveland, 1988b) were used to measure perceived workload during the tasks.



Figure 84: Two body positions for piloting the drone with DJI FPV equipment (head-mounted display and remote control): upright and supine.

Data were analyzed by a one-way repeated measures ANOVA, with body position as a factor (upright or supine). We added the order of positions and the operator's experience as between-subject factors. All Post Hoc analyses were performed with a Bonferroni correction. All 14 subjects were included in the analysis for the inspection task. However, for the instruction task, two subjects were removed from the analyses because they were not native French speakers, and the instructions were given in French, and as post-task interview showed their mistakes were due to the language understanding.

20.3 | Results

Influence of body position on mean speed in the inspection task

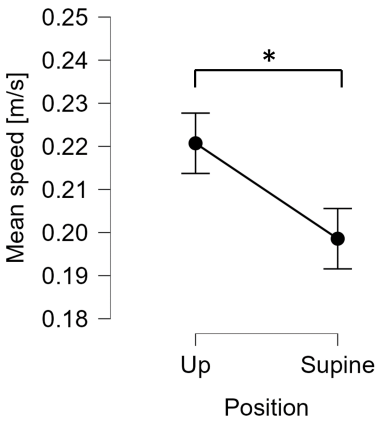

Figure 85: Effect of body position on mean travel speed during the inspection task. Error bars represent the standard errors ($^*p < .05$).

Results revealed a significant main effect of **Position** on mean travel speed ($F_{1,13} = 5.00$, $p = .043$, $\eta_p^2 = .278$) during the inspection task. Post hoc comparisons showed that operators in the supine position moved the drone more slowly ($p = .043$) (Figure 85).

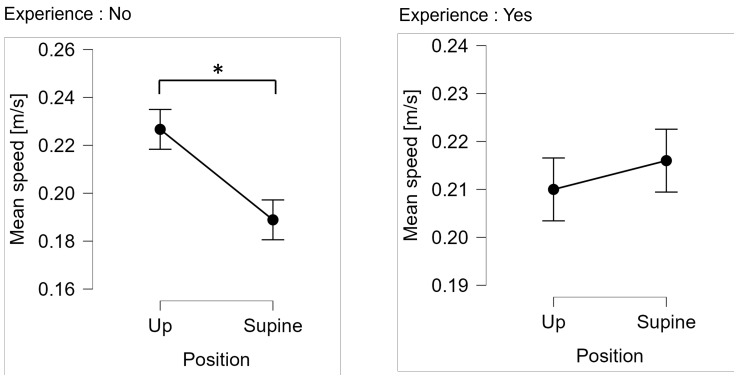

Figure 86: Interaction of body orientation and operator's experience on mean speed during the inspection task. Error bars represent the standard errors ($^*p < .05$).

Furthermore, a significant interaction of **Position** $\times$ **Experience** was found regarding the mean travel speed ($F_{1,12} = 6,33$, $p = .027$, $\eta_p^2 = .345$). Post hoc analyses revealed that participants with no experience were significantly influenced by body position, which was not the case for experienced participants (Figure 86).

Influence of position order on performance perception, distance to station and speaking duration

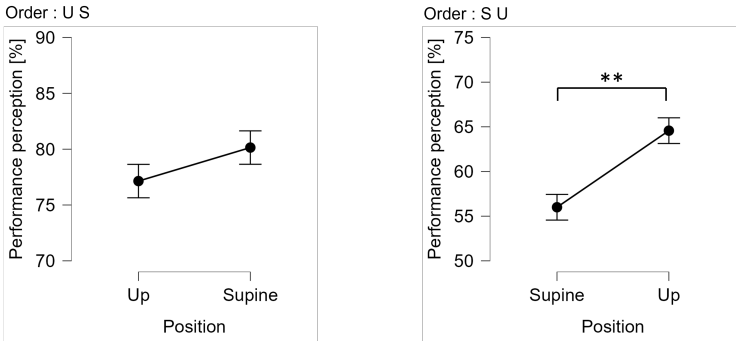

Figure 87: Interaction of body orientation and position order on performance judgment. Error bars represent the standard errors ($^*p < .01$).

We found a significant interaction of **Position** $\times$ **Order** on performance judgment ($F_{1,12} = 15,55$, $p = .002$, $\eta_p^2 = .564$) collected via the NASA-TLX form. Post hoc analyses revealed that perception of performance increased significantly between the first and second exe-

cution of the task for participants starting in the supine position (Supine then Upright), whereas this was not observed in the other order (Upright then Supine) (Figure 87).

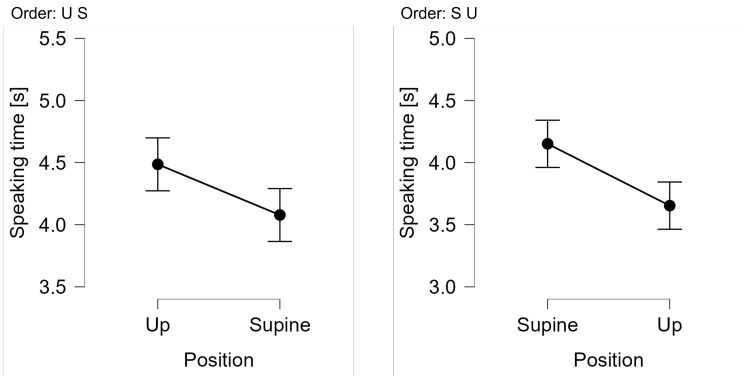

Figure 88: Interaction of body position and position order on speaking time to identify anomalies. Error bars represent the standard errors.

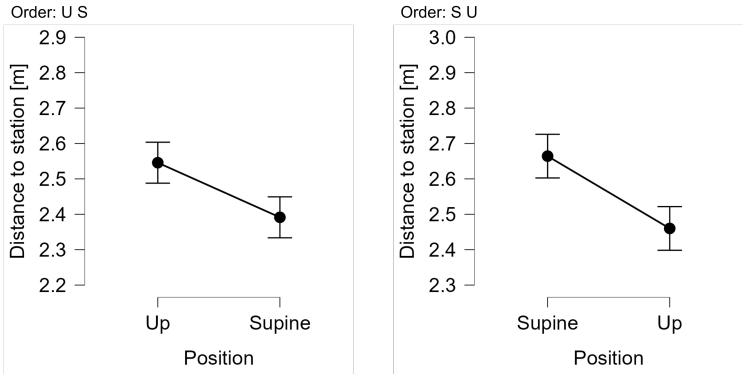

Figure 89: Interaction of body position and position order on the distance to the station.

Furthermore, results revealed a significant interaction of **Position** $\times$ **Order** on distance to station ($F_{1,12} = 8.90$, $p = .011$, $\eta_p^2 = .428$) (Figure 89) and on speaking time ($F_{1,12} = 5.03$, $p = .045$, $\eta_p^2 = .295$) (Figure 88). Both measures decreased significantly during the second repetition of the task.

Instruction execution task

There was no effect of position on the number of incorrect movements, nor was there any effect of the words used. No axis was found to have a greater effect on the number of errors.

20.4 | Discussion

In this study, we set up an experimental protocol to investigate how body position impacts visual detection and teleoperation performance. Although our hypothesis based on the literature suggested that performance would decrease in the supine position, our findings couldn't confirm it. It might reflect a coping mechanism to maintain performance and further study with neuro- and physiological computing is needed to understand the underlying mechanism. Also, no significant effect of body position was found regarding our participants' performance in the inspection or the instruction execution task.

What's particularly interesting in the results is that operators make the drone move more slowly in the supine position than when standing upright. Literature findings could partly explain this result. Indeed, in one of their studies, McManus and Harris (2021) conducted an experiment using virtual reality that assessed how much visual motion was required to evoke the perception that the participant had reached the position of a previously presented target. They observed that the participants overestimated the covered distance. This could be interpreted as the operators feeling they were moving faster. Another hypothesis may be the one advanced by Kim et al. (2022) to justify the perception of the size of objects, which turns out to be greater during tests conducted in the supine position. They suggested that perception of distance and size may be impaired in the supine position due to increased vulnerability to perceived threats, thus influencing perception. For instance, studies have shown that threat-related stimuli, such as spiders, are perceived as larger and closer by people who feel threatened or vulnerable (Fessler and Holbrook, 2013; Vasey et al., 2012). In our context, the supine position could have increased the operators' feeling of vulnerability, leading them to perceive that they were moving faster than in reality and, therefore, to slow down the drone's speed as a precaution.

Interestingly, descriptive statistics showed that only participants new to drone piloting flew significantly more slowly in the supine position. This difference could be explained by how much mental effort is required to handle conflicting sensory information. According to Bock (1998), dealing with alternated gravitational environments requires many mental resources to adapt to these new conditions, similar to learning new skills. For novice participants, a significant part of their cognitive load is dedicated to learning the basics of drone piloting. Consequently, they have fewer mental resources to effectively manage the additional challenge of visuo-vestibular conflicts. In contrast, experienced participants familiar with drone control can allocate more cognitive resources to resolving these conflicts. This helps to explain why experienced participants are less affected by the supine position as they have the mental capacity to manage the conflict without being overwhelmed by the primary task of piloting the drone.

Regarding the significant difference in perceived performance for participants who first performed the task in the supine position, several factors could contribute to this effect. Due to visuo-vestibular conflicts, participants may initially find the supine position

more challenging and demanding regarding cognitive load (Muehlhan et al., 2014). When switching to the upright position, which is more familiar and less demanding, they may perceive a significant improvement in performance due to the relative ease compared to their initial experience.

The observed decrease in speaking duration and distance to the station during the second repetition of the task can be attributed to an order effect. Participants continue to learn and adapt during their first execution of the task. This continuing learning process likely makes them more familiar with the task requirements and the anomalies they must identify. As a result, participants are more efficient at identifying anomalies during the second execution, making their verbal responses more fluid and concise. In addition, increased familiarity with the task and environment likely increases their confidence, allowing them to approach the station more closely. This pattern aligns with the principles of motor learning and adaptation, where repeated exposure and practice led to improved performance and efficiency (Shadmehr and Mussa-Ivaldi, 1994). Therefore, the significant interaction effect of position and position order on both speaking duration and distance to the station highlights the importance of task repetition in the improvement of operator performance.

Limits To our knowledge, this is the first study to investigate the impact of body position on the teleoperation performance of a real drone. Some limitations can be addressed in future work. The sample size (N=14) could be increased to include balanced groups of experienced and novice teleoperators. Also, the experimental environment and equipment introduced several constraints. The drone (DJI FPV) was originally designed for outdoor use. This led to frequent visual and auditory alerts when the drone was too close to the ceiling or the ground, which could distract participants and affect their performance. Additionally, the drone had a slight drift to the right, requiring participants to correct its position. This may have introduced an additional element of complexity, particularly for novice pilots. The language barrier during the instruction execution task, conducted in French, may have affected non-native speakers' performance. Furthermore, the sensitivity of subjective and behavioral measurements may not have been sufficient to detect subtle differences in performance between the upright and supine positions. More precise instruments and methods of neuroergonomics (such as eye movements, cardiac and neural activity monitoring) could provide a more accurate assessment of the effect of body position on teleoperation performance and human-robot interaction, in general (Roy et al., 2020).

Perspectives Considering the significant order effect that was observed, a potential solution to mitigate this would be to have a longer training or to increase the number of repetitions of the task for each condition. As part of future research on the execution of instructions, it would be interesting to measure the reaction times between the moment the person hears the instruction and the moment they execute the movement. This requires

the use of a highly precise time synchronization tool. In addition, it would be beneficial to conduct studies with larger and more diverse groups of participants to increase the generalization of the findings. Including participants with different levels of drone piloting experience and age groups could provide a more comprehensive view of the factors influencing teleoperation performance in different body positions.

HIGHLIGHTS

1. Through an ecological experimental protocol, this study investigated whether the visuo-vestibular conflict induced by the supine position impacts performance in the teleoperation of a real drone when performing an inspection task.
2. Our results showed that although overall performance was not significantly affected by body orientation, behaviors such as reduced drone speed in the supine position.
3. Furthermore, our results indicated that only novice pilots, participants with no experience in drone FPV teleoperation, were affected by the supine position.
4. These findings are valuable for understanding the influence of body orientation on teleoperation performance and highlight the importance of adaptation and learning.

21 | Chapter conclusion

This chapter presents several innovative experimental protocols designed to address our research questions on the impact of dynamic environments, modified force fields, and robot visualization perspectives on teleoperators' performance and experience while ensuring a high level of ecological validity. In this sense, the protocols were more representative of the real-world conditions teleoperators face in terms of the dynamic environment (Exp IV), the specific conditions of operations in confined and isolated environments (Exp III), as well as the nature of the task and the target population (Exp V). These protocols were designed to answer the following research questions :

1. Does the supine position impact teleoperation, and how is it affected by an isolated and confined environment over time? Does the type of visual perspective (1PP vs. 3PP) reduce or compensate for the negative effects of the supine position and confined environment? (Exp III)

2. Do load factors induced by aircraft turns impact teleoperation? Does spatial incompatibility between the directions of the aircraft's turn and that of the controlled robot further impact teleoperation? Does the type of interface visualization reduce or compensate for the negative effects related to the operator's body movements? (Exp IV)

3. Does the supine position impact the teleoperation of a real drone from a first-person perspective during an inspection task? (Exp V)

The initial results collected from the experiments conducted on board an aircraft with load factors (Exp IV), as well as those involving the teleoperation of an FPV drone in a supine position (Exp V), indicate that teleoperation remains robust, whether in virtual or real scenarios. No differences were observed between 1PP and 3PP visualization conditions. However, the supine position appears to induce behavioral changes in drone control among novice participants, notably reducing the drone's average speed. Additionally, high load factors led to a decreased user experience, as indicated by increased mental and physical demands, along with symptoms of motion sickness. Furthermore, results collected from the spatial analog environment were unusable, possibly due to insufficient preparation, lack of motivation and engagement, and/or communication or instruction issues, highlighting the difficulties associated with conducting experiments in remote or analog space environments.

These protocols represent a significant advancement, being among the first to demonstrate the feasibility of conducting controlled experimental studies in environments such as aircraft or analog space settings and using real drones. The insights gained from these initial studies not only help delineate the protocols' limitations but also pave the way for future research opportunities.

GENERAL DISCUSSION

We now move on to the general discussion of this manuscript. Following each experiment, the obtained results were interpreted and discussed, assessing the extent to which the findings supported or challenged the specific hypotheses. In this final chapter, we will adopt a broader view of our results.

After summarizing the findings, we will dive into the discussion related to our main research questions. The first part of the discussion will address the impact of dynamic environments on teleoperation. The organization will be based on categories of measures collected throughout the experiments, including behavioral, performance, and subjective experience measures. The main results from the various experiments will be compared and interpreted in light of existing literature, and the practical implications for teleoperation will be examined by evaluating the extent to which our conclusions can be generalized to other areas of teleoperation and providing recommendations for future studies. The subsequent section will explore teleoperation interfaces designed for dynamic environments. General findings will be presented and interpreted, with a primary focus on the impact of visual perspective on teleoperation. The practical implications of these results will also be discussed, along with recommendations for future research. This section will conclude by considering alternative interface types that may be relevant to the research questions. Finally, our discussion will conclude with an examination of the work's general limitations and a proposal of directions for future research.

22 | Summary of overall results

This thesis lies at the intersection of fundamental and applied research. Our goal was to gain insights into the impact of dynamic environments on teleoperation and to propose a visualization interface that would compensate for or reduce the detrimental effects of these environments. Our research questions were as follows: *Does the operator's body tilt and motion affect performance and user experience in teleoperation? Does the spatial incompatibility of motion and tilt directions between the operator's body and that of the robot further impact teleoperation performance and user experience? Does the type of visualization help reduce or compensate for the negative effects related to the operator's motions?*

To answer these questions, we developed experimental protocols capable of demonstrating, for the first time, the effect of dynamic environments on the performance of different teleoperation tasks. These protocols allowed to compare teleoperations between moving and static conditions, to investigate the effects of spatial compatibility and incompatibility between the operator's body movements and the expected movements of the teleoperated unit, and to test different types of visualization interfaces to find the most suitable for these dynamic teleoperation contexts. These experiments were conducted in two ways, first, in a controlled laboratory setting with a large number of participants to ensure the reliability and robustness of our results. Secondly, more realistic studies, closer to the actual work conditions of teleoperators, were conducted to ensure the ecological validity of the lab results and to see if they could be replicated in real-life settings.

The first experimental block focused on the effect of spatial incompatibility between the movement directions of the operator's body and that of the robot's on teleoperation performance. Results showed that when the operator's body movement directions are spatially incompatible with those of the remotely controlled robot, teleoperation performance is impaired, and reaction time increases. **The second block** continues exploring the impact of spatial incompatibility and compares these results with teleoperation under static conditions. It also examines whether a visualization interface for the distant robot could mitigate the negative effects of dynamic environments. The results suggest that dynamic environments do indeed affect teleoperation. Specifically, we found once again that spatially incompatible movements impaired robot control. Furthermore, regardless of spatial compatibility, when their bodies are in motion, operators tend to initiate robot control earlier, while their cognitive, physical, and mental demands, as well as levels of motion sickness, increase. The results also indicated that using a 3PP view reduced these negative effects on both teleoperation outcomes and user experience. **The third and final block** of this manuscript presents experimental protocols designed to investigate whether the effects observed in the laboratory can be transferred to more ecological contexts. These protocols were developed to study teleoperators in more realistic conditions, including during analog space missions, under different load factors on board an aircraft, and during the

teleoperation of a real drone for inspection tasks. Preliminary results showed that in more ecological settings, teleoperators tend to adapt to their environment to maintain their teleoperation outcomes. However, behavioral changes such as slower robot control, increased perception of physical and mental demands, and higher levels of motion sickness were observed. Figure 90 provides an overview of the main results.

Effect of operator's body tilt and motion

Measures	*Performance*	*Behavioral*	*Subjective*
Exp I	Compared to SC, SI Motion ↓ Accuracy (AE), in the manual-control task	Compared to SC, SI Motion ↑ RT and ↓ Precision (std) in the manual-control task	SC Tilt ↓ post choice confidence in the perception tasks
Exp II	Compared to N, SI Motion ↓ Accuracy (AE)	Compared to N, Motion ↓ TTR50 Motion ↓ TTR70	Compared to N, Motion ↑ Mental demands Motion ↑ Physical demands Motion ↑ Motion sickness
Exp IV	ns	ns	Compared to 1g, 1,9g ↑ Mental demands 1,9g ↑ Physical demands 1,9g and 1,3g ↑ Motion sickness
Exp V	ns	Compared to N, Mean speed ↓ only in Non expert	ns

Effect of visual perspectives

Measures	*Performance*	*Behavioral*	*Subjective*
Exp II	Compared to 1PP, 3PP ↑ Accuracy (AE + shooting in the opposite direction)	Interaction effect 1PPC : Undershoot 3PPC : Overshoot 1PPC ↓ manual movement quantity	Compared to 1PP, 3PP ↓ Mental demands 3PP ↓ Physical demands
Exp IV	ns	ns	ns

Figure 90: Summary of Ph.D. results This table presents a summary of the key findings from this research. *Abbreviations*: "SI Motion" refers to spatially incompatible motion directions, while "SC Motion" refers to spatially compatible motion directions. "N" indicates that the chair was in neutral position, meaning no motion or tilt was applied. "ns" denotes a nonsignificant result, implying no significant effect of body tilt, motion, or visual perspective on the corresponding measure was observed. The results of Exp III were not included in the summary due to unusable data (Section 18).

23 | Impact of dynamic environments on teleoperation

As explained Section 11, in this manuscript, teleoperation was evaluated through both objective and subjective measures. The objective measures are divided into two categories, the behavioral measures and the performance measures. We acknowledge that performance measures could be considered a subset of behavioral measures; however, for the sake of clarity and readability, we chose to separate them. Here, for us, *behavioral measures* include all metrics related to the kinematics of movement, such as movement timing, average speed, reaction time (RT), task completion time, and time to reach a certain percentage of the target angle (TTR). *Performance measures* reflect success indicators relative to the teleoperation task objectives presented to the participants. This includes the degree of error between the target angle and the achieved angle (angular error, AE), as well as the number of detected impacts compared to the actual number of impacts. *Subjective measures*, on the other hand, refer to the operator's experience, such as perceived mental or physical demands (evaluated using items from the NASA TLX), post-choice confidence, and the level of symptoms experienced, such as motion sickness or cybersickness.

The following sections will discuss the impact of dynamic environments on teleoperation in light of our results on behavioral, performance, and subjective measures.

23.1 | Behavioral measures

Speed accuracy trade-off

When comparing operators' behavior in a normal to a modified force field, for two different teleoperation tasks (real vs. virtual, robot orientation task vs. visual inspection task), we observe that participants tend to adopt different robot control strategies. When their bodies experience rolling movements, they start controlling the robot (moving at a constant speed) earlier (Exp II), and in a supine position, they slow down the drone's speed to perform the inspection task (Exp V). These two changes in behavior appear to serve a similar goal: allowing operators more time to complete the same task.

Similar trends have been found in the literature. Taking more time to perform visuomotor tasks, mainly pointing tasks or interacting with a touchscreen, in dynamic environments has also been repeatedly reported (Cowings, 1999; McDowell et al., 2005; Metcalfe et al., 2008; Rider et al., 2003a,b; Salmon et al., 2011; Truszczynski et al., 2013). In these studies, this trend could manifest as slower manual movements, increased task completion times, or prolonged phases of the manual movements. For example, in their studies Rider et al. (2003a,b) aimed to assess the effects of a moving ground vehicle on operators performing in-vehicle push-button reaching. Their experiments showed how the two phases of a pointing movement—the ballistic initial phase and the final adjustment phase—can be affected by a moving environment. Their results revealed longer final adjustment phases and

increased fingertip displacement during this phase. According to the authors, during the adjustment phase, "*the operator attempts to compensate for the ride motion by taking additional time to steady the arm as the finger nears the button*". Slower movements and longer reaction times were observed in other altered force fields, such as microgravity (Bock et al., 2010; Mechtcheriakov et al., 2002; Weber et al., 2016). Furthermore, in Exp IIb, we found that participants took more time to execute movements in a task where the robot's speed was automatic and constant. As a result, to save time, they were forced to anticipate and start the control earlier. These results are consistent with work by Bertucco and Cesari (2010), which shows that the CNS anticipates and initiates postural adjustments earlier when a task is perceived as more complex.

Taking more time to execute a complex movement is a well-documented strategy employed by the CNS to maintain high performance, known as the Speed Accuracy Trade-off (SAT). It suggests that the final precision of a response varies depending on the time taken to execute it. This effect was first introduced in 1899 by Woodworth (1899) (reviewed in Heitz (2014)), but a well-known formulation of this relationship was later introduced as the Fitts' Law; this law models human movement by showing that during rapid pointing tasks, the more difficult the task (i.e., smaller or more distant targets), the slower the movement to maintain accuracy (Fitts, 1954). This relationship has also been observed using various controllers such as computer mice, joysticks, and gamepads (Jagacinski et al., 1980; Kantowitz and Elvers, 1988; Ramcharitar and Teather, 2017).

Differences between novices and experts

Interestingly, in Exp V, we observed that only novice participants in FPV drone piloting showed a slowdown in the drone's average speed. These findings align with the work of Beilock et al. (2008) which demonstrated that novices in golf exhibited a classic speed-accuracy trade-off when performing a series of putts (a highly precise golf task). Novices slowed their movements during the planning and execution phases to enhance their performance, whereas experienced golfers maintained their speed without sacrificing accuracy. The authors argue that this could be because novices must devote more explicit attention to learning the necessary skills and procedures, while experts have automated many cognitive processes, allowing them to perform accurate movements more quickly.

These results can also be explained by the mental effort required to manage conflicting sensory information. As Bock (1998) noted, "*dealing with altered gravitational environments requires significant cognitive resources to adapt to these new conditions, similar to learning new skills*". For novice participants, much of their cognitive load is dedicated to mastering the basics of drone piloting. As a result, they have fewer mental resources available to effectively handle the additional challenge of visuo-vestibular conflicts. On the other hand, experienced participants familiar with drone control can allocate more cognitive resources to resolving these conflicts. This explains why experienced participants are less affected by

the supine position, as they have the mental capacity to manage the conflict without being overwhelmed by the primary task of piloting the drone.

Are cognitive processes more complex in dynamic environments?

The time taken to initiate a response, as well as the execution time of the response during cognitive tasks, are both known to be affected by the same factors and provide insight into the duration of the mental processes involved in completing the task (Abrams and Balota, 1991; Balota et al., 1989). Longer reaction and response times are associated with longer and more complex cognitive processes (Fitts, 1954; Heitz, 2014). Consequently, these behavioral changes seem to indicate that dynamic environments may disrupt cognitive processes during teleoperation tasks. What existing hypotheses in the literature explain why mental processes are more complex when performing visuomotor tasks in dynamic settings?

McDowell and his colleagues conducted experiments to address the human factor issues for Manned Ground Vehicles, mobile control bases from which military personnel must perform operations on touchscreens and computer interfaces (McDowell et al., 2005, 2007), see Section 9. According to them, performing visuomotor tasks on board moving vehicles may require more complex cognitive processes for two main reasons: i) First, due to the intersensory conflict caused by the lack of external visual reference points outside the vehicle. ii) Second, because of the increased variability of stimuli and responses in these environments. After analyzing their results, they attributed their outcomes primarily to the uncertainty associated with the vehicle's movements. They state that: "*The motion environments introduce variability not only in the final position of the targets but also in the orientation of the participants relative to gravity. This configuration requires a highly adaptive and dynamic movement planning process*". Thus, the responses required in such an environment become multiple and uncertain. This uncertainty leads to an increase in the possible options for executing a movement. They connect this idea to Hick's and Hyman's work, which posits that the more choices available in a task, the longer the reaction time (RT) will be (Hick, 1952; Hyman, 1953). For instance, in a task where a participant must press a button corresponding to a light, the more buttons there are to monitor, the longer it will take to select the correct response. In other words, RT increases linearly with the number of choices or the "uncertainty" related to the appearance of the next stimulus.

Although McDowell and colleagues primarily explain these results by the uncertainty due to the vehicle's movements, other research also shows that intersensory conflicts can increase reaction times during visuomotor tasks. For example, Drugowitsch et al. (2014) studied the implications of multisensory integration in decision-making tasks; they stated that: "*bounded* (sensory) *evidence accumulation explains decision accuracy, speed, and certainty*" and showed that when sensory information indicating the same event is contradictory, reaction time increases.

Moreover, a hypothesis related to the existence of internal models could also explain why exposure to altered gravito-inertial environments complicates cognitive processes during movement execution. Bock and collaborators explained that exposure to a modified gravitational-inertial environment, such as that observed in microgravity, leads to sensorimotor discrepancies due to the use of inadequate internal models (Bock, 1998; Bock et al., 2010). During action execution, the sensory feedback obtained does not match the expected sensory feedback (provided by motor efference copy) (Section 7). It is then necessary to adapt these internal models for them to be effective in this new force field. Bock compares this active adaptation mechanism to that implemented during the learning of new motor skills, a process that is also highly resource-intensive in cognitive terms and would explain the longer reaction times in microgravity.

Impact of incompatible movement directions

Now, let's compare participants' behaviors between the spatially compatible and incompatible movement directions. The results from experiment Exp Ib revealed a longer reaction time during the teleoperation task that required getting to the target angle as quickly as possible. These results are consistent with studies illustrating the deleterious effects of incompatibility between a stimulus and its response on reaction times (Eriksen and Eriksen, 1974; Simon and Rudell, 1967; Stroop, 1935). More specifically, Simon's studies demonstrated the effects of spatial compatibility and incompatibility between the stimulus and its response (Simon and Rudell, 1967; Simon and Small Jr, 1969), as well as between a distractor irrelevant to the task and the response (Simon and Craft, 1970) (see Section 10).

However, these behavior changes were not observed in our second virtual teleoperation task used for Exp IIb and Exp IV. Indeed, in this teleoperation task, the subject's objective was not to reach the target as quickly as possible but to reach it at the right moment while the robot advanced autonomously. If an incompatible movement direction affected cognitive processes in these conditions, it was not reflected in our behavioral data analyses. However, as explained in the section below, which discusses the effects of dynamic environments on performance, the effects of spatial compatibility were felt on accuracy performance in both of our laboratory tasks (Exp I and Exp II).

Implications for Teleoperation

To conclude, our behavioral analyses showed that teleoperating in modified force fields leads to a trend toward longer execution times, in line with the speed-accuracy tradeoff principle (Fitts, 1954; Heitz, 2014). These observations also align with those of other studies conducted on board moving vehicles (Cowings, 1999; McDowell et al., 2005; Metcalfe et al., 2008; Rider et al., 2003a,b; Salmon et al., 2011; Truszczynski et al., 2013). Additionally, in experiment Ib, we observed longer RTs when the operator's body motion direction was spatially incompatible with that of the controlled robot. These results are con-

sistent with stimulus-response compatibility theories (Simon and Rudell, 1967; Simon and Small Jr, 1969) and presented in Section 10.

As longer reaction and completion times are associated with complex cognitive processes (Abrams and Balota, 1991; Balota et al., 1989; Fitts, 1954; Heitz, 2014), we can infer that dynamic environments seem to increase the complexity of the tasks at hand, forcing the teleoperator to take more time to maximize precision (SAT). In incompatible movement directions situations, reaction times appear to be even longer compared to compatible situations, suggesting that these conditions potentially increase the level of complexity. Their impact on performance will be discussed in the following section.

Furthermore, the SAT principle shows that task time and difficulty influence precision (Fitts, 1954; Heitz, 2014). Hence, since dynamic environments already render teleoperation tasks more complex, adding factors that increase complexity or imposing a time constraint in these conditions could have an even more negative effect than in static environments. This underscores the importance of designing teleoperation interfaces to be as intuitive and ergonomic as possible to reduce task complexity and mitigate the impact of the speed-accuracy tradeoff on teleoperation. Furthermore, as our results (and those from the literature) show, the differences between novices and experts could suggest that adequate training, allowing individuals to reach a sufficient level of expertise, could limit the adverse effects of these environments (Beilock et al., 2008).

23.2 | Performance measures

The problem of incompatible movements

Teleoperation performance does not seem to be affected by all types of movements in the same way. Indeed, when comparing participants' performance in situations where the direction of movements is compatible or incompatible with the manual movements required for robot control, we observed that only situations involving incompatible movement directions negatively impacted the teleoperators' performance. This effect has been observed in Exp Ib and Exp IIb, that s to say in tasks requiring the control of a single element of the robot as well as for those requiring full robot control. It manifests when the robot is both static and in motion. Moreover, this effect is present in both trial-based control and more continuous control. Finally, it appeared independent of whether the visualization was from a 1PP or 3PP.

These results are consistent with those obtained during a concept demonstration conducted by the Lead System Integrator of the military program Future Combat System, presented in Chen et al. (2007). The demonstration focused on controlling a robotic vehicle from a moving command vehicle, and the researchers found that teleoperators were also affected by incompatible movement conditions, as they *"tended to oversteer their robotic vehicles when their own vehicle was turning one way but the robot needed to turn the other way"* (Chen

et al., 2007). Unfortunately, we were unable to obtain the full report of this demonstration. The detrimental effects of opposite movement directions on precision in manual control are supported by studies illustrating the negative effects of incompatibility between a stimulus and its response on reaction times (Eriksen and Eriksen, 1974; Simon and Rudell, 1967; Stroop, 1935), and more specifically, Simon's studies that show the effects of spatial compatibility and incompatibility between the stimulus and its response (Simon and Rudell, 1967; Simon and Small Jr, 1969), as well as between an irrelevant distractor and the response (Simon and Craft, 1970) (see Section 10).

An interesting explanation of the Simon effect is related to attentional allocation. In a review, Hommel (2011) explains this theory: "*People might have a primitive tendency to react toward the source of stimulation, a kind of orienting reflex (...) that facilitates actions towards, and interferes with actions away from the stimulus*." He adds that "*This consideration actually consists of two components. For one, it presupposes some sort of attentional response to the stimulus, which is presumably automatic, and, for another, it assumes that this response somehow facilitates spatially corresponding reactions*". A study by Kaliuzhna et al. (2019) could support this theory in relation to our experiment. Indeed, using a classic Posner cue-to-target task paradigm, Kaliuzhna shows that passive rotation can be used as an exogenous or endogenous attentional cue and can orient attention in space. The results indicate that when bodily rotation is used as an exogenous cue, i.e., when sensory stimuli are unexpected, the onset of rotation alters reaction times: responses are quicker in congruent trials and slower in incongruent trials. Moreover, when bodily rotation is presented in an endogenous manner, i.e., when participants are explicitly informed that the direction of rotation will predict, in the majority of trials, the side of target appearance, cues in congruent trials facilitate responses, while no inhibitory effect is found for incongruent trials. Therefore, it is possible that, in our experiment, bodily movement attracted participants' attention in one direction, and that if the manual movement to be performed had to go in the opposite direction, this would not only complicate but also delay the spatially corresponding reaction (that is orienting the robot in the opposite direction), thereby impacting reaction time and precision.

Implications for teleoperation

The results from the behavioral measures, along with those from performance measures, suggest that dynamic environments induce the need for more complex cognitive processing, pushing the operator to take more time to maintain the same level of precision (Fitts, 1954; Heitz, 2014; Woodworth, 1899). This is manifested in our experiments by a behavioral change associated with maintained performance when movements are compatible. However, as soon as the task becomes more complex, such as in situations where the operator's body movements are incompatible with those of the robot, the level of complexity reaches a threshold such that the time needed to achieve accuracy is no longer sufficient, negatively impacting performance.

This detrimental effect of incompatible movements has been observed in our two laboratory studies. We attempted to replicate these situations in a more ecological environment (Exp IV). However, under the load factor induced by the aircraft's turns, gravity was perceived as aligned with the participants' longitudinal axis, preventing the perception of bodily inclination and, consequently, the effects of spatial compatibility. Therefore, to generalize these results to more ecological contexts, several aspects could be explored. First, we tested inclination only along the roll axis; it would be relevant to test on other axes of movement. Second, the observed effect should be evaluated in tasks of varying nature and complexity, as well as in different ecological contexts. Third, our study was limited to teleoperation using a head-mounted display, where operators are deprived of the view outside the vehicle. However, in many teleoperation cases from moving vehicles, operators have a visual reference of the outside world; for instance, the teleoperation scenario presented by Airbus for Exp IV, (Airbus, 2018), which could reduce visuo-vestibular conflicts (Raffi and Piras, 2019); thus, it is essential to examine this aspect. Finally, our tests were conducted using only a gamepad. It would be beneficial to test different types of controllers, as, for example, the use of a joystick may have different effects than those of a gamepad, due to the forces required for pulling and pushing, which influenced our results in the Exp Ia.

23.3 | Subjective measures

Two studies allowed us to compare the experiences of teleoperators in static and dynamic environments. Whether using a motion platform in the laboratory (Exp II) or in a more realistic context under the load factor induced by the movement of an aircraft (Exp V), results are similar: in a dynamic environment, participants report a less favorable experience, both in terms of mental and physical demands as well as levels of motion sickness.

Mental and physical demands

In line with our results, the literature also reports high cognitive mental and physical demands when exposed to dynamic environments and/or altered gravity. For example, motion induced by a vehicle has been associated with an increase in perceived physical demands (NASA-TLX item) during control tasks in highly automated vehicles (Sadeghian Borojeni et al., 2018), as well as an increase in the overall cognitive workload of passengers performing tasks interacting with computer interfaces (Cowings, 1999; Goode et al., 2012; Salmon et al., 2011). Furthermore, hypergravity has been associated with decreased cognitive performance (Albery, 1989; Ercan and Gunduz, 2020; Levin et al., 2007), and numerous studies have also documented an increase in workload under altered gravity conditions, especially in microgravity (Bock et al., 2003, 2010; Casler and Cook, 1999).

Motion Sickness

Our results showed that performing a task from a moving vehicle, using a head-mounted display or a tablet, induces motion sickness. These observations align with the findings of Cowings (1999); Iskander et al. (2019); McDowell et al. (2007); McGill et al. (2017, 2020), who reported similar outcomes during screen-based tasks performed in moving vehicles. Additionally, they are consistent with literature that highlights the link between intersensory conflicts and motion sickness (Bertolini and Straumann, 2016; Iskander et al., 2019).

When examining the average ratings given by participants regarding their motion sickness symptoms, we found that these symptoms were significantly lower in Exp IV, where a tablet was used on board the aircraft, compared to Experiment IIb, conducted with an HMD on a motion platform. In Experiment IV, motion sickness symptoms were rated at 15% for the highest load factor (1.9g) and 6% for level flight (1g), while in Experiment IIb, they reached approximately 17% with no movement and 23% for conditions with movement. Although our results did not allow us to determine if this reduction in symptoms was due to the different origins of motion sickness (potential contribution of the Coriolis effect in Experiment IV). They remain consistent with the study by Kuiper et al. (2018), which showed that an interface allowing peripheral visibility of the outside world from a moving vehicle can reduce intersensory conflicts and, consequently, motion sickness symptoms.

Implications for Teleoperation

Dynamic environments appear, both in our experiments and in the literature, to increase subjective mental and physical demands as well as symptoms of motion sickness. These effects have been observed when performing dynamic teleoperation tasks (i.e., moving the robot in its environment) for different teleoperation scenarios, whether viewing the robot via an immersive HMD or on a tablet placed above the cockpit of an aircraft, allowing the operator to see the outside world peripherally and thus be aware of the vehicle's motion.

To generalize these results to other types of teleoperation tasks, it is necessary to conduct experiments measuring mental and physical demands as well as motion sickness symptoms when performing teleoperation tasks involving the visualization of static scenes. This would help determine whether these effects also transfer to tasks such as monitoring via a map-type interface or controlling/monitoring a static robot performing manipulation tasks. Indeed, while dynamic visual scenes are particularly known to induce more cybersickness than static scenes (Metzulat et al., 2024), several studies have all reported motion sickness symptoms and a higher workload when performing tasks requiring the visualization of static scenes from moving vehicles (Cowings, 1999; Iskander et al., 2019; McDowell et al., 2007; McGill et al., 2017, 2020). Hence, there is a need to examine whether the adverse effects on teleoperators' subjective experience also manifest in tasks requiring observation of a more static interface.

Moreover, it is important to note that our results show that an affected subjective workload measure does not necessarily link to a decrease in performance. For instance, Exp IIb showed that both performance and subjective workload measures were impaired, while Experiment IV showed an increase in subjective workload without any decrease in performance. It is not uncommon to observe discrepancies between workload subjective scale, physiological and performance-based measures (Matthews et al., 2020). To better understand this gap, it would be relevant to investigate the mental state of the operator using additional (and multiple) objective measures (Williges and Wierwille, 1979).

This can be achieved for instance by collecting an indirect measure of workload, evaluating the operator's performance on a secondary task (Young et al., 2015). If the operator easily performs both tasks simultaneously, it indicates that the primary task is not too demanding. However, if performance on the secondary task is impacted, it suggests that the primary task is too demanding, and cognitive resources cannot be allocated to the secondary task without degrading performance. This measure is interesting because it is objective, though it has its limitations. In line with Wickens' multiple resource theory, "*Secondary tasks are explicitly designed to probe "residual capacity" not used for a primary task*" (Wickens, 2002). Thus, to correctly assess workload using this method, the secondary task must compete for the same type of cognitive resources as the primary task (Casner and Gore, 2010). In our case, if the primary task is a monitoring task, it is necessary to select a secondary task that requires similar visual attention rather than an auditory task, for instance, which would engage a different modality and thus be less competitive. However, teleoperation tasks are often multisensory by nature—the operator may need to listen to the radio, follow orders from superiors, and simultaneously visualize and control the distant robot. In such cases, designing a secondary task becomes complex, as it should theoretically tap into the same resources while ensuring that it does not interfere with the primary task (Young et al., 2015). Moreover, if the teleoperation scenario involves multitasking, this method can be quite relevant. However, for other types of scenarios, it may not accurately reflect real-life conditions. Another objective measure of workload can be extracted from physiological data (Matthews et al., 2020; Young et al., 2015). For instance, workload and mental fatigue can be associated with measurable physiological markers from sensors such as electroencephalography (EEG), electrocardiography (ECG), oculometry, or electrodermal activity (EDA) (Ahn et al., 2016; Roy et al., 2020; Shaffer and Ginsberg, 2017; Tao et al., 2019; Trejo et al., 2015) (Section 3.2). These physiological measures do not alter the nature of the teleoperation task, unlike the secondary task methods. They could provide valuable insights into the underlying effects of dynamic environments, helping to ascertain whether there is an actual increase in cognitive effort or if it is simply a subjective perception from the participant.

24 | Teleoperation interfaces for dynamic environments

24.1 | Effects of visual perspective

The 1PP and 3PP visualization interfaces were tested in dynamic environments in the laboratory (Exp IIb) and on board an aircraft under different load factors (Exp IV). For these two experiments, participants continuously controlled the orientation of a virtual robot.

Laboratory results (Exp IIb) showed that the 3PP improved both teleoperation performance and the subjective experience of operators (mental and physical demand), regardless of the operator's movement condition. This indicates that the 3PP reduced the negative effects observed due to the chair movements. As explained in the discussion of Exp IIb, these results are indeed consistent with previous studies that also demonstrated that 3PP is better suited for navigation and dynamic tasks (Bhandari and O'Neill, 2020; Temma et al., 2019; **?**; **?**), and enhances spatial awareness between oneself and surrounding elements (Covaci et al., 2015; Gorisse et al., 2017; Ueyama and Harada, 2022). These competencies were indeed central to our virtual teleoperation task, which required a good estimation of one's speed, the distance between the operator and the target (obstacle), and the orientation of the obstacle in the environment to know at what angle to orient the robot to succeed in the task.

However, the beneficial effects of 3PP visualization were not observed aboard the aircraft (Exp IV). Although comparing Exp IIb and Exp IV is challenging due to differences in protocol and the number of participants, the teleoperation tasks themselves were similar, making it interesting to note certain observations. In Exp IV, there was no significant effect of load factor on performance, no notable changes in participants' behavior, and the subjective experiences of the teleoperators were comparable (mental and physical demands) or even improved (lower ratings of motion sickness symptoms) compared to those in Exp IIb. These differences may suggest that the teleoperation task was perceived as less cognitively complex when performed in Exp IV. Yet our experimental protocols did not allow us to determine whether these differences resulted from the differences in dynamic environments (load factor vs. roll movement), the teleoperation scenario (HMD vs. tablet), a mixture of both, or from adjustments made to the experimental protocol to adapt it to the aircraft environment.

However, as discussed in the previous subsection regarding the impact of dynamic environments on motion sickness, the literature supports that performing a task in a moving vehicle, with a peripheral vision toward the outside helps reduce visuo-vestibular conflicts, which we also found in our results (motion sickness symptoms were on average higher in Exp IIb while wearing an HMD compared to Exp IV). It may be hypothesized that in Exp IIb, the dynamic environment and, more specifically, the visuovestibular conflict it induced when using an immersive interface (HMD), could have affected participants' spatial perception (as discussed in the literature presented in Section 8), and that the 3PP improved

their spatial perception in such situations. In Exp IV, the peripheral vision of the vehicle's movements could reduce the intersensory conflict, thus making the 3PP less necessary. If this hypothesis is correct, it would suggest that in dynamic environments, a teleoperation interface with a screen at eye level and a view toward the outside would be preferable to using an HMD. If an external view is impossible, then a 3PP perspective to visualize the robot could be advantageous. However, further research comparing teleoperation performance using these two interfaces (tablet and HMD) and perspectives (1PP/3PP) in the same dynamic environment is necessary. Additionally, incorporating supplementary workload measures (physiological or through a secondary task) could provide further objective evaluation of workload, allowing for a deeper understanding of these phenomena.

24.2 | Proposed interface improvements

In this manuscript, we proposed using a 3PP interface to support spatial perception of the remote environment during teleoperation. Another approach could be to create interfaces that decrease the teleoperators' workload. Interestingly, numerous studies provide guidance on designing ergonomic and intuitive interfaces and controllers aimed at reducing perceived workload to improve teleoperators' experience and performance (Section 4). These recommendations have been formulated to optimize the subjective experience and performance of teleoperators in static environments. However, our results, supported by the literature, show that in the specific context of teleoperation from dynamic environments, motion sickness symptoms add an additional dimension that impacts subjective experience. Furthermore, there appears to be an interesting relationship between motion sickness and workload. Indeed, the literature indicates that motion sickness tends to significantly increase workload (Irmak et al., 2021; Metzulat et al., 2024). An excessively high workload is often synonymous with increased fatigue and decreased performance (Arsintescu et al., 2020; Bruggen, 2015; Fan and Smith, 2017). Therefore, an interesting lever for reducing the perceived workload of operators in a dynamic environment would be to focus on designing interfaces that alleviate motion sickness symptoms. Below, we will introduce various interfaces designed to reduce motion sickness and the strategies employed, while also exploring potential applications for teleoperation.

Display Placement The placement of visual displays plays a significant role in mitigating motion sickness. According to Kuiper et al. (2018), higher display positions that maintain peripheral visual cues of the vehicle's motion induce less motion sickness compared to lower positions that limit these cues. In their study, participants performed a visual search task on a screen positioned either at eye level in front of the windshield, which allowed for substantial peripheral view through the window, or at glove box height, which offered diminished peripheral vision. The authors hypothesized that increased peripheral vision alleviates motion sickness, a hypothesis supported by their findings. They state that: "*Hav-*

ing a completely unobstructed view of the earth-fixed world around the vehicle is the quintessential way to reduce motion sickness following visual-vestibular incongruences". The authors further explain that peripheral vision is crucial for self-motion perception (Raffi and Piras, 2019). Consequently, having a peripheral view of the external environment provides visual cues that align with vestibular information, thereby minimizing the visuo-vestibular conflicts that contribute to motion sickness.

Visual cues Incorporating optical flow that aligns with vestibular signals is required for reducing motion sickness. For instance, Feenstra et al. (2011) suggest that "*the use of similar artificial presentations of a fixed Earth reference frame and future motion trajectories could provide effective means to reduce motion sickness in automated vehicles*". In their experiment, participants experienced airplane turbulence in a flight simulator under three different visual stimulation conditions. The first condition involved viewing only the cabin's interior; the second presented a fixed star field on Earth that moved coherently with physical motion (i.e., in the opposite direction of self-motion); and the third condition involved star movements that anticipated the movement of the turbulence. Their results indicated that while standard artificial imagery could reduce motion sickness by a factor of 1.6, the anticipatory condition significantly mitigated symptoms, yielding a factor of 4.2. This method, using a fixed Earth reference frame, was also recently proposed by Apple as a new accessibility feature to reduce motion sickness symptoms when using their phone or tablet in a moving vehicle (Apple Newsroom, 2024).

The role of visual information, such as optical flow that aligns with vestibular input and aids in anticipating vehicle movements, presents a promising avenue for designing teleoperation interfaces aimed at minimizing motion sickness and potentially reducing workload. However, many teleoperation tasks involve piloting or monitoring a robot from a first-person perspective, requiring operators to estimate the robot's speed and position based on the optical flow provided by the visual interface (Section 1). This could lead to the presentation of dual optical flow information. Consequently, two critical questions arise:

1. Could the simultaneous presentation of two different optical flow signals still induce motion sickness?

2. If motion sickness is alleviated, might this dual information compromise the perception of the robot's movement?

For instance, Brandt et al. (1973) found that conflicting central and peripheral optokinetic stimuli (i.e., stimuli rotating in opposite directions) can impair exocentric visual motion perception, affecting the sensation of self-motion within a stable environment. The authors suggest that this impairment may stem from *the increase in speed of moving retinal images caused by the optokinetic nystagmus going in the opposite direction* (Brandt et al., 1973). If the perception of environmental motion in peripheral vision is compromised in situa-

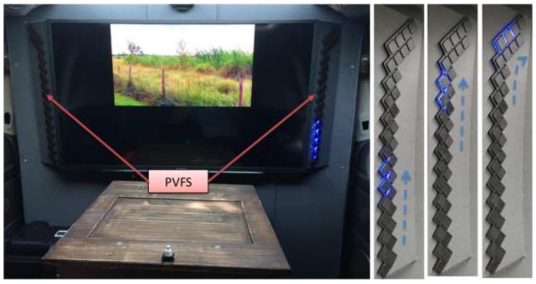

Figure 91: "Peripheral visual feedforward system (PVFS): (a) Positioning inside the Mobility Lab; (b) Lights are moving from bottom to top on the right side to indicate that the fully automated vehicle is about to turn to the right." from Karjanto et al. (2018)

tions with conflicting central and peripheral visual stimuli, then in dynamic environments, peripheral visual information may conflict with vestibular signals. In such cases, visuo-vestibular conflicts and motion sickness symptoms would likely persist. Further studies are required to investigate whether the perception of the robot's movement through central vision could be affected by these methods aimed at reducing motion sickness. Nonetheless, these techniques remain relevant for teleoperation scenarios where the interface does not convey optical flow, such as when controlling a static robot or tracking a moving robot on a map.

In another study, Karjanto et al. (2018) demonstrated that different types of anticipatory information about vehicle movements, which do not correspond to optical flow, can also be presented on the visual interface to mitigate motion sickness. Their "*Peripheral Visual Feedforward System (PVFS)*" provided information about the vehicle's upcoming actions, such as turns, in the peripheral attention of participants (Figure 91). While watching a video, participants focused on the PVFS to anticipate the vehicle's movements. This system successfully reduced motion sickness symptoms. However, this interface puts the operator in a multitasking situation, known to decrease performance (for instance Lin et al. (2016)). Interestingly, the researchers assessed mental workload during the primary task with and without the PVFS, finding no significant differences. They still, however, emphasized the importance of ergonomics for this tool to minimize cognitive resource consumption: "*the information given by the PVFS needs to be very rich in information yet intuitive and straightforward so that digesting and understanding it should be quick and intuitive.*"

Various other methods have been proposed to reduce motion sickness in automated vehicles by focusing on sensory cues. These include visual, haptic, and auditory signals to anticipate vehicle movements, as well as odors aimed at minimizing motion sickness. In terms of car design, guidelines have been suggested regarding seat posture, temperature, and ventilation, along with recommendations for the vehicle's construction, such as advanced suspension technologies and adapting driving dynamics to passengers' activities (see Pereira et al. (2023) for a recent review).

3PP and operator head movement integration with camera control Furthermore, Griffin and Folmer (2019) explored a method to reduce cybersickness during locomotion phases in a virtual reality game. Normally, to avoid cybersickness induced by optical flow in first-person view, players use teleoperation. In their study (Griffin and Folmer, 2019), the authors propose testing what they call out-of-body locomotion, which corresponds to a 3PP view. Additionally, they implemented something very interesting in VR: in addition to the 3PP visualization of the avatar, they ensured that "*the user can always look around, and the camera pivots and moves based on the physical rotations and translations observed on the VR headset*." The authors explain that "*since this generates vestibular afferences, it generally does not induce cybersickness*." They demonstrated that there was no difference between the teleoperation and 3PP navigation method conditions, which were both associated with a very low level of cybersickness. This method could be useful for teleoperation using head-mounted displays, particularly from a moving vehicle. Just as we integrated the head movements of the operator into our virtual environment to limit sensations of cybersickness in Exp II, it would be interesting to implement a camera that can move independently of the robot (without interfering with the robot's movements) and whose movements correlate with the head movements of the operator controlling the robot remotely. This would allow for the incorporation of the operator's head movements into the distant environment, reduce intersensory conflict, thus limiting motion sickness, and also increase situational awareness, as the operator could control the camera independently of the robot's direction.

Designing interfaces that help mitigate motion sickness and reduce the cognitive load of remote operators in dynamic environments could ensure optimal performance and teleoperation experience. To achieve this, the field of autonomous vehicles can be particularly valuable, as there is increasing research on the impact of vehicle motion on the performance and well-being of passengers performing tasks unrelated to driving. Moreover, this field offers tools, interfaces, and methods to alleviate motion sickness. Studies suggest that two strategies are effective: the first involves reducing intersensory conflicts between the visual and vestibular systems by providing visual input regarding the vehicle's motion; the second allows passengers to anticipate the sensory consequences of the vehicle's movements. It is noteworthy that a lack of anticipation of the vehicle's movements and intersensory conflicts have also been blamed for increasing the complexity of cognitive processes, leading to longer reaction times and potentially resulting in decreased performance (see Section 23.1). Future research should investigate whether these interfaces designed to limit motion sickness could also enhance reaction times and performance in the context of teleoperation. These solutions hold promising potential, though the application of these solutions should be approached with caution, as non-driving tasks may remain very different from teleoperation tasks. Additionally, studies evaluate motion sickness but do not necessarily measure performance in tasks performed inside the vehicle.

As explained in Section 4.6, designing interfaces suited for teleoperation missions requires a thorough understanding of the challenges operators face, and creating human-

robot interfaces and interactions tailored to those challenges to minimize performance degradation. As outlined in Section 4, various challenges can affect teleoperation, which may be related to the individual characteristics of the operator (who), the nature of the task to be performed (what), the robotic system used (how), the remote robot's environment (where), and the operator's environment (wherefrom). Regardless of the challenge, a personalized and effective way to maintain performance is to monitor the operator's cognitive state through physiological computing as well as its behavior in real-time to prevent any decline by proposing interface adjustments tailored to the task, scenario, and teleoperation context. Physiological and behavioral data about the operator's state are sent to the robotic system, which monitors this information. Once a critical threshold is reached, nearing a point associated with performance decline, the robotic system offers the operator a different human-robot interface or interaction. This well-known approach has been shown to increase situational awareness, reduce mental workload, and maintain performance (Bailey et al., 2006; Singh et al., 2022; Wilson et al., 2000). Our research shows that dynamic environments can lead to a decrease in operator performance and subjective experience, and that using a 3PP visualization can help mitigate these negative effects during navigation tasks. Similarly to physiological computing, in teleoperation within a potentially dynamic environment, transmitting information about the operator's surroundings to the robotic system could allow the system to offer an interface better suited to that context (Figure 92). To achieve this, further research is needed to precisely determine the critical threshold at which performance may decline (e.g., certain types of motion, such as horizontal acceleration variations in a vehicle, are more likely to induce motion sickness than others (Iskander et al., 2019)), and to test different types of teleoperation interfaces, which will likely need to be tailored to each specific task.

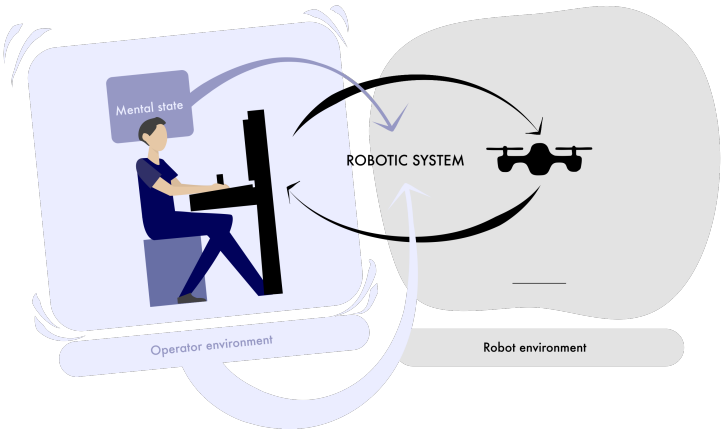

Figure 92: Representation of a teleoperation system utilizing operator physiological and environmental data to adapt human-robot interaction

25 | General limitations and perspectives

While specific limitations and their corresponding perspectives have been discussed earlier in the context of the research questions, it is essential to also highlight some more general limitations of this work that may inform future research directions. Future research can advance in several key areas, including the inclusion of expert participants, the diversification of teleoperation tasks and scenarios, the enhancement of performance measures, the integration of physiological assessments, and the incorporation of more ecologically valid motion. These directions are explored in greater detail below.

Use of Game Controllers and Laterality In our experiments, we primarily used game controllers, and participants were required to use their right hand to control the robot. The majority of our participants were right-handed, which rendered it less relevant to conduct a specific study on left-handed individuals, given their low representation in our samples. However, it would be beneficial to carry out further studies by recruiting a significant number of both left-handed and right-handed participants to compare their performance, particularly in relation to spatial compatibility effects.

Non-Expert Participants Most of the studies were conducted with non-expert participants in teleoperation. Both the literature and our findings suggest that experts may exhibit different behaviors. Therefore, it would be crucial to replicate these experiments with expert participants. Moreover, the cognitive learning process appears to be highly task-specific, making it interesting to have experts perform familiar operations from their professional environments, but transposed into a dynamic setting. This approach would allow us to assess the transferability of their expertise in these environments and compare their performance to that of novices.

Diversity of Tasks and Teleoperation Scenarios To address our research questions, we selected the capabilities most likely to be affected in the studied environments based on the scientific literature and designed simplified teleoperation tasks to observe whether these capabilities were indeed impaired. However, teleoperation tasks and scenarios are numerous and varied. Therefore, additional studies are needed to evaluate whether our findings can be generalized to other types of teleoperation tasks, potentially more complex and with different requirements.

Performance Measures Our performance measures primarily focused on the operator's perception and manual control of the robot, which are very specific aspects of teleoperation. However, in teleoperation, the operator must not only control the robot accurately according to mission objectives but also maintain a broad situational awareness (see Section 3.3). For instance, in a navigation task, we assessed the operators' ability to maneuver

the robot correctly to avoid obstacles. Yet, in real-world situations, the operator must perform this task while maintaining awareness of broader factors, such as the route to follow, the robot's battery status, and other mission goals. A future research direction could be to design a task that measures this broader situational awareness. This could involve creating or utilizing a teleoperation task with more general objectives and diverse constraints. For example, the TELEOP task, developed at ISAE-SUPAERO and used to evaluate the impact of confinement and isolation on crew performance during teleoperation activities, could help address this limitation. It involves controlling a virtual rover to collect a sample from the lunar surface. Participants have a map showing the sample's location and must choose a route, reach the collection point while avoiding craters, and manage the remaining time. They then precisely manipulate the rover's robotic arm to grab the sample without dropping it and place it correctly. Performance is thus evaluated based on a task that combines both navigation and manipulation, with local and global measures.

Ecologically Valid Dynamic Environments The movements induced in our lab and flight experiments were chosen in a controlled manner to evaluate the effect of spatial compatibility while maintaining a dynamic yet predictable environment. It is possible that participants anticipated these movements. However, a key feature of dynamic environments is the unpredictability of vehicle movements, both in terms of direction and intensity, and the ability to predict external forces is fundamental for executing accurate body movements. Therefore, this unpredictability should be integrated into future studies to better reflect real teleoperation conditions in more ecologically valid environments.

26 | Conclusion

This Ph.D thesis has revealed essential insights into teleoperation from dynamic environments, a critical area for future missions in sectors like space exploration and defense.

Our findings have shown that dynamic environments can impair teleoperation. When the operator's body movements are incompatible (opposite) with those of the teleoperated unit, control ability diminishes. Regardless of the movement direction, the mental and physical workload experienced by the operator, as well as motion sickness, increase, and behavioral changes are observed, suggesting a tendency to take more time to control the robot. Additionally, our research revealed that introducing a 3PP interface helps reduce some of these negative effects, suggesting that better interface design could greatly enhance both precision and the operator's overall experience.

These results highlight the need for continued research, both fundamental and applied, to better understand the effects of dynamic environments and to refine interfaces, to optimize teleoperation performance in these varied and challenging environments.

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