Acta Astronautica 217 (2024) 382–392

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

AstroAccess: Testing accessibility accommodations for disabled and mixed-ability crews operating in space-like environments

Jamie L. Molaro[a,*], Ann Kapusta[b], Sheri Wells-Jensen[c], Anna Voelker[d], Sina Bahram[e], Tim Bailey[f], Dana Bolles[g], Mary Kate Cooper[h], Christy Fair[f], Michael Fauerbach[i], Lisa Gethard[j], Sheyna E. Gifford[k], Jody Greenhalgh[l], Eric Ingram[m], Sumant Jha[n], Raja Kushalnagar[o], A.J. Link[p], Austin A. Mardon[q], Gaurav Mathur[o], Mona Minkara[r], Viktoria Modesta[g], Caitlin A.L. O'Brien[s], Zuby Onwuta[t], Sawyer Rosenstein[g], Eric Shear[u], Shivani Varia[g], Apurva Varia[g], Erik S. Viirre[v], George Whitesides[w], Brenda R. Williamson[v], Herbert R. Zucker[x]

[a] Planetary Science Institute, 1700 E. Ft Lowell Rd, STE 106, Tucson, AZ, 85719, USA
[b] ThinkSpace Consulting, USA
[c] Bowling Green State University, USA
[d] SciAccess, Inc, USA
[e] Prime Access Consulting, Inc, USA
[f] The SpaceKind Foundation, USA
[g] Unaffiliated, USA
[h] Stanford University, USA
[i] Florida Gulf Coast University, USA
[j] Trident Technical College, USA
[k] St. Louis University, USA
[l] Stanford University Medical Center, USA
[m] 5199 LLC, USA
[n] Zephyrus Research, USA
[o] Gallaudet University, USA
[p] Center for Air and Space Law, USA
[q] University of Alberta, USA
[r] Northeastern University, USA
[s] The Ohio State University, USA
[t] Think and Zoom, USA
[u] University of Florida, USA
[v] University of California San Diego, USA
[w] Whitesides Foundation, USA
[x] HR-ZTECH, LLC, USA

ARTICLE INFO

Keywords:
Accessibility
Disability
Human spaceflight
Space habitats
Astronauts
Universal design

ABSTRACT

Society today is experiencing a golden age of robotic space exploration and interest in human spaceflight has regained popularity as entities like NASA and the burgeoning private space industry refocus attention on sending humans back to the Moon and into orbit. This is a critical turning point for society, as some look to our future as a possibly spacefaring civilization while others wonder who will be enabled to participate in that space exploration. Historically, Disabled individuals and other minoritized groups have been excluded from space science and technology fields, as well as from participation in astronaut programs. However, human space exploration can be made more inclusive with research and innovation in the area of accessible design. Universal accessible design brings advantages to all individuals operating in an environment, and the ability of Disabled individuals to adapt to environments not suited for them can be leveraged as a strength in spaceflight. In this work, disabled and mixed ability crews performed research on parabolic zero-gravity flights which produce weightlessness,

* Corresponding author.
E-mail address: jmolaro@psi.edu (J.L. Molaro).

https://doi.org/10.1016/j.actaastro.2024.02.012
Received 19 April 2023; Received in revised form 5 October 2023; Accepted 9 February 2024
Available online 10 February 2024

exploring tools and technologies which may mitigate challenges for disabled individuals operating in space-like environments. Here we discuss the experiments performed on our flights, highlighting what types of technologies offer promising solutions for accessible design of space habitats, suits, and tools, and accommodations which can enable future disabled astronauts to operate safely in space. We will highlight universal design solutions that not only provide access to previously excluded researchers but have the potential to improve safety and efficiency for all astronauts, regardless of disability. We will also discuss operational strategies which can be incorporated into training and procedure to leverage the strengths of mixed ability crews in ensuring everyone operates effectively together.

1. Introduction

The triumph of human spaceflight has inspired generations of scientists, artists, and enthusiasts to imagine a future where the ability to explore and experience space becomes a part of life on Earth. Many see human settlement of other worlds as the next stage in our growth as a civilization, others envision research stations on the Moon and Mars to enable scientific exploration and ecological conservation of their landscapes. Whatever reason may inspire an individual, collective interest at a societal level has spawned a burgeoning private space industry and ignited broad discussion about both human and commercial activities. The National Space and Aeronautics Administration (NASA) is working to return humans to the Moon in this decade, and astronauts from other public and private entities may not be far behind.

Due to the extreme cost and difficulty in getting there, private corporations currently hold some of the largest influence in both inspiring and enacting space activities, and their actions are necessarily driven by profit rather than human ideals, whether aimed at space tourism, resource utilization, or something else. With a lack of regulations to limit corporate activities, major conflicts have already arisen between different sectors of society with differing views on our purpose and conduct in being there. This emphasizes the need for more inclusive access to space, and to the jobs and roles which have influence over both enabling and limiting that access. If we, as a society, are going to send humans into space for any purpose, it is critical that Disabled individuals and other marginalized groups participate in defining the narrative of our relationship with it, how and why we explore it, and who is included in exploration activities. Further, more than 1 in 10 humans lives with a disability or functional adaptation [1], and space exploration as many envision it will require their support to be successful. This work addresses a critical gap by performing research to enable participation by Disabled individuals.

Historically, Disabled individuals have been excluded from human spaceflight opportunities in both the public and rapidly growing private sector due to perceptions that they lack the physical endurance or capacity to function in extreme environments, ability to perform rigorous or dexterous athletic activity, or the ability to operate effectively as part of a team with nondisabled individuals. Such perceptions are born from broadly pervasive and harmful societal assumptions about their ability to act and live independently, and from the lack of motivation on the part of individuals and institutions to invest in making the necessary modifications to our physical environments and daily behaviors required to make society more accessible. These assumptions are self-perpetuated by the fact that lack of accessible pathways to science and engineering careers leads to a decreased representation of Disabled individuals who succeed in these communities [2,3].

In this work, we posit that with reasonable accommodations, as well as proper training for both disabled and nondisabled crew members, Disabled individuals would not only be capable of performing the duties of an astronaut but would bring unique strengths to the role. To date, little research has been done to investigate how different disabilities may influence function in space environments or effective design principles for space vehicles and habitats. To this end, AstroAccess works to advance research on disability and human spaceflight by flying Disabled researchers (the “Ambassadors”) on parabolic flights which produce weightlessness. The Ambassadors carry out investigations to test accessibility accommodations that may assist future disabled astronauts operate in the extreme environment of space. To date, AstroAccess Ambassadors have participated in five parabolic flights. This study describes the results from the first two, which took place in October 2021 and May 2022. We will outline the basic goals and operational processes for AstroAccess flights, the experiments performed during each flight, and outcomes. We will also discuss general implications for human spaceflight and promising directions for future research.

1.1. Language

The language people use surrounding identity and disability status is nuanced, complex, and often personal. In this paper, we use the term “disability” as opposed to “handicapped, impaired” or other quasi-synonyms because it is the term preferred by the majority of the disabled community. However, we note that some people, in particular who identify as Deaf and/or neurodivergent, do not use any of these terms to describe themselves. Additionally, there are two widely used conventions for referring to disabled people: person-first language (e.g., "people with disabilities”) and identity-first language (e.g., "Disabled people") [4,5]. Individual preference is a matter of personal and political choice. We use primarily identity-first language because we feel it most clearly generalizes the narrative of the research for a broad audience, and because the importance of Disability as a personal and cultural identity to many people in society is relevant to the motivations and broader implications of the work. Readers may also note mixed use of capitalization in words like disabled, blind, or deaf throughout the text. A capital word is used in cases where identity is relevant or being denoted, whereas lowercase words are used where the word acts primarily as a medical descriptor. The latter is used in the majority of the text which describes the experiments and their outcomes. A person can be considered disabled if they have a physical or intellectual condition that substantially limits one or more major life activities [6] or their access to one or more aspects of society. For our purposes, we specifically exclude people who are sick with reasonably short term, temporary illnesses (e.g., a cold), injuries (e.g., a broken arm), and mental and emotional afflictions (e.g., a person in mourning).

1.2. Background

The first astronauts at NASA selected for Project Mercury in 1959 were military personnel chosen for their physical fitness, experience in piloting aircraft, and background in engineering. At that time, they were also required to be less than 40 years old, as well as shorter than 5 feet 11 inches in order to fit into the Mercury spacecraft. However, NASA recognized the value of incorporating diverse backgrounds into flight crews and, for later missions, expanded the search to include those with science and medical degrees. The current requirements for astronaut candidacy in the United States are to: be a US citizen, possess a master’s (or equivalent) degree in a STEM (science, engineering, technology, and math) field, have two years of professional experience or 1000 h of pilot-in-command time on a jet aircraft, and be able to pass the NASA flight astronaut physical. The physical encompasses some direct physical restrictions, such as a visual acuity of 20/20, limited eye pressure, and a height between 62 and 75 inches. However, more broadly but indirectly, it screens out many disabled individuals because it is designed explicitly to be performed by what it considers to be an "able" body. For example, balance related tests that require standing could not be completed by someone without lower limb control, or a hand-eye coordination test completed by someone who is blind.

Yet, research shows that disabled individuals who participate in training and physical activity achieve higher levels of physical fitness than their inactive counterparts, when measuring factors such as muscular strength, cardiorespiratory response, hand-eye coordination, and endurance [7–10]. If both a disabled and nondisabled individual can be considered physically fit to some medical standard, the remaining factors by which one could include or exclude a person from astronaut candidacy boil down to: *what condition of the disabled individual's mind or body limits or inhibits their ability to accomplish a given task, is it necessary that every astronaut making up a crew are able to perform this task independently, and is it necessary that they are capable of performing this task without reasonable accommodations?* To the latter question, some aspects of mission design and infrastructure have always been modified for individuals on NASA missions, such as tailoring space suits and seats to their bodies. Within healthy parameters, astronauts select which foods they will eat, allowing for individual variation, exercise regimes, and the kind of emotional support accessed are adjusted to meet each astronaut's needs. If such individualization is reasonable for nondisabled astronauts, then implementing accommodations for disabled astronauts may be equally routine. However, it is fair to say that what disability accommodations may be considered reasonable is not yet well understood because more research is needed to understand what accommodations are needed to make it accessible, which is part of what motivates this study.

Inherent within these questions is the broad practical theme of what tasks make up a job description and how well suited an individual may be to it. For example, if a person's sole job is to fly an airplane, it is not necessarily practical to find some accommodation that allows blind individuals to safely land one in case of computer failure. In contrast, astronaut duties vary widely within physical, intellectual, and skill-based spheres, and where a candidate may have one weakness, they may also have valuable strengths. Ultimately, all astronauts must undergo physical conditioning and skill training to learn how to pilot and function aboard a spacecraft, and to plan and prepare for how to mitigate weaknesses in performance of their duties. Additionally, it is natural that all individuals have strengths and weaknesses, and the makeup of a team can leverage that diversity to the advantage of the mission. The strengths which disabled individuals can bring to such a team should be explored.

This is evident in NASA's own history as the human spaceflight program took shape in the 1960s. The "Gallaudet Eleven" were deaf men recruited by NASA to undergo research on the effects of spaceflight on the body. Since they had sustained damage to their vestibular systems, they were immune to motion sickness and therefore able to endure physical challenges while being subjected to rotation, high acceleration forces, and weightlessness they may experience in space without becoming nauseous [11,12]. Unfortunately, this very advantage which made them excellent candidates for research would have disqualified them from applying for astronaut candidacy. Studies show 60–80% of astronauts experience motion sickness which can adversely affect the performance of their duties when adjusting to microgravity and on return to Earth [13,14], suggesting candidates lacking susceptibility to it would strengthen a team. In other examples, studies show that dyslexic and blind individuals tend to excel at tasks requiring creative thinking [15] and serial memory [16], respectively, relative to their nondisabled counterparts which could aid them in performing numerous types of tasks on board a space station. More broadly, since many Disabled individuals are already adept at adapting to physical environments that are not suited to them [17,18] and have developed psychosocial resilience [19,20], this may lay a strong foundation for the problem-solving skills and emotional endurance required for human spaceflight.

While no public space agency has yet to "officially" fly a Disabled astronaut, individuals with conditions that may be considered disabilities in some contexts have been to space, including Rich Clifford (1997) with early signs of Parkinson's, Scott Kelly with ADHD, and Haley Arceneaux (2020) with an artificial femur. Numerous other astronauts have sustained injuries or been affected by conditions which have temporarily disabled them [21], some in ways which disabled individuals live daily. It is also worth noting that at the end of a long duration mission, any astronauts who have been in microgravity for an extended period of time do not possess the same strength and agility as they did when beginning the mission. It was unremarkable, for example, for astronauts to be carried off the shuttle or be lifted from the Soyuz vessel. Even those who manage to walk out have measurably impaired strength, balance and coordination among other deficits [22]. While similar health issues may prevent a person from being recruited to begin a mission, all of these professional astronauts were presumably "fit" to perform their duties during their time in space until the day they left orbit. This begs the question of whether "fitness" under terrestrial gravity is necessarily a good measure of what is needed to operate in space. As NASA and other public space agencies begin to expand their criteria for astronaut candidacy and as the private sector begins to envision their future customer base, such considerations will need to be made. Some agencies have begun this process, for example the European Space Agency announced and selected a disabled individual for a "Parastronaut Feasibility Study" in 2022, though its outcome remains to be seen. More research must be done on what risk previously inadmissible characteristics actually incur in space environments, and whether those risks warrant exclusion of disabled individuals from human spaceflight or whether they can be reasonably overcome.

1.3. Broad goals

AstroAccess has several broad goals, which are to: (1) demonstrate that disabled individuals can independently and safely function in weightlessness, (2) test strategy- and technology-based accommodations to enhance functionality while operating or performing tasks in weightlessness, (3) perform research which can facilitate better accessible design in the development of space environments, including spacecraft and habitats intended for human operation and occupancy, (4) influence the policies of public and private space entities surrounding requirements for astronaut candidacy, and (5) inform the development of training programs and operational strategies for disabled and non-disabled astronauts in both their own duties and in their need to work cohesively together.

2. Methods

2.1. Ground and flight crews

For this study, Disabled Ambassadors with a variety of backgrounds and disabilities were selected to fly on each flight. Our primary flight (referred to as Flight "AA1", Table 1) had a crew with twelve Ambassadors (Fig. 1), all but one of whom had never been on a zero-gravity flight before. In May 2022, AstroAccess had five guest seats aboard a flight by partner organization the Aurelia Institute ("Aurelia", Table 1). All of the Ambassadors on Aurelia had previously flown on Flight AA1. In addition to the Ambassadors, research support members joined the crew on each flight. The support crew aided in the completion of various experiments, for example, by handing an object to an Ambassador, orienting their body in a specific position, or recording data.

When selecting Ambassadors, we specifically recruited individuals with disabilities in three broad categories: Blind/Low Vision (Blind/LV), Deaf/Hard of Hearing (Deaf/HH), and mobility disabilities. These categories do not represent the full spectrum of types of disabilities, but it was necessary to limit the scope of our efforts given the small size of the

Table 1
Table of Experiments
Experiments and research areas investigated on the flights. The primary flight is referred to as Flight AA1 and the partner flight is referred to as Aurelia.

Line of Investigation	Experiment	Research Category	Flight	Disability Group
ASL Communication	ASL vs Orientation	Communication	AA1, Aurelia	Deaf/HH
Blind/LV Navigation	Haptic Nav - Handheld Ultrasonic	Navigation & Translation	AA1	Blind/LV
	Haptic Nav - Wearable Ultrasonic	Navigation & Translation	AA1	Blind/LV
	Light Perception Sensing	Navigation & Translation	Aurelia	Blind/LV
	Sound Beacons	Navigation & Translation	AA1	Blind/LV
	Tactile Navigation	Navigation & Translation	Aurelia	Blind/LV
Blind/LV Communication	Braille Display	Communication	AA1	Blind/LV
	Slate & Stylus	Communication	AA1	Blind/LV
	Hands-Free Image Enhancer	Communication	AA1	Blind/LV
Flight Suit & Prosthesis Modifications	Leg Straps	Functional Environment	AA1	Mobility
	Prosthesis Harness	Functional Environment	AA1	Mobility
	Magnetic Prosthesis	Functional Environment	Aurelia	Mobility
Mobility-Restricted Movement	Station Keeping	Navigation & Translation	AA1, Aurelia	Mobility
	Point-To-Point Movement	Navigation & Translation	AA1, Aurelia	Mobility
	Prostheses Removal/Replacement	Functional Environment	AA1, Aurelia	Mobility
Universal Aids	Handholds & Footholds	Functional Environment	AA1, Aurelia	all groups
	Haptic Signaling (Gravity Status)	Communication	AA1	Deaf/HH, Blind/LV
	Light Signaling (Gravity Status)	Communication	AA1, Aurelia	Deaf/HH
Universal Operations	Leaving/Returning to Home	Navigation & Translation	AA1	all groups
	Station Keeping	Navigation & Translation	AA1	all groups

Fig. 1. Ambassadors Pre-Flight
Ambassadors standing proudly and smiling in front of the Zero-G plane before boarding. From left to right is (top row) Mary Cooper, Dr. Sheri Wells-Jensen, Eric Shear, Apurva Varia, Sina Bahram, Zuby Onwuta, Dr. Mona Minkara, Viktoria Modesta, (bottom row) Sawyer Rosenstein, Dana Bolles, Eric Ingram, and Ce–Ce Mazyck. The four individuals in front are seated in wheelchairs, the two standing Ambassadors flanking the group each have visible prosthetic legs, and one of the blind Ambassadors is holding a white cane.

flight crew and the initial questions we wished to investigate. Of our team of twelve, three Ambassadors had low vision with varying degrees of light perception and one was fully blind. Two Ambassadors were deaf. The remaining six Ambassadors had various types of mobility disabilities. Note that the term "mobility disability" is applied here as a shorthand to generalize a group of individuals with disabilities that all relate to mobility in some way. However, we emphasize that their conditions differ widely such that this generalization may lack meaning in other contexts and do a disservice to individuals. Of these Ambassadors, four used wheelchairs and had limited to no control over lower limbs, and three of them used leg or arm prosthetics.

The broader AstroAccess team consists of ~50 individuals involved primarily on a volunteer basis, with expertise in space, research, design, and medicine. Disabled individuals are represented on the team at all levels, including leadership, sub-committee chairs, Ambassadors, and research leads. The experiments planned for each Ambassador during the flights were developed with input from both Disabled team members (including the Ambassadors themselves) and other team members with disability expertise, including rehabilitation physicians, occupational therapists, and consultants from disability related organizations. Our medical team worked individually with mobility disability Ambassadors to discuss specific needs with respect to plane ingress/egress, practical training, motion sickness, in-flight safety, and flight recovery. Research and design experts helped guide experiment methodology and outcomes.

2.2. Flight plan and description

The investigations performed for this study were done on a series of commercial flights operated by the Zero-G Corporation (Zero-G). The Zero-G aircraft flies in a parabolic trajectory that allows passengers to experience weightlessness. The experience has been likened to the weightless sensation that can occur while riding a roller coaster but is executed in a more controlled and precise manner. A flight consists of a set of number of parabolas, each of which produces approximately 20 s of weightlessness. Flight AA1 consisted of fifteen parabolas and Aurelia had twenty. Individual flight plans were developed for each Ambassador and included one or more experiments. Experiments could span a single or multiple parabolas and could be performed individually, with other Ambassadors, or with a member of the support crew.

The short duration of weightless periods is one of the primary challenges in executing zero-gravity investigations, as it requires tasks to be performed very quickly. To acclimate passengers to the physical sensation of low gravity and prevent motion sickness, it is typical for the first parabolas of each flight to approximate martian gravity (approximately one-third terrestrial gravity), followed by two at lunar gravity (approximately one-sixth terrestrial gravity) before moving on to weightlessness. Even with acclimation, the sensation of weightlessness can be disorienting and physically and/or emotionally overwhelming. To prepare, Ambassadors worked with ground crew and support crew to practice and test equipment for each experiment ahead of the flight.

The inside of the aircraft features several rows of normal airplane seats in the rear of the cabin, with the rest of the cabin in front of the seats open with a padded floor. Prior to the AA1, yoga mats were attached to the floor in the open area to represent suborbital spaceflight seats and designate "home" locations for each Ambassador. On both flights, straps and cords were attached to the walls, floor, and ceiling to use as hand and footholds (Fig. 2). Safety requirements during takeoff and landing dictated that not everything could be installed ahead of time, and anything affixed to the cabin interior was inspected by the

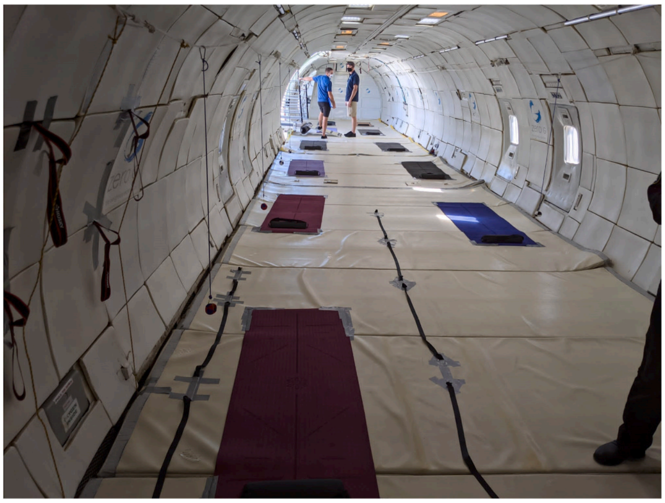

Fig. 2. The Zero-G Aircraft (left) View of the aircraft cabin ahead of Flight AA1 showing a long, white, open tube with padded walls and floor. A large door is seen on one side of the craft letting light inside, and two individuals are conversing in the background. Cables, straps, and footholds are visible duct taped to the cabin walls and floor, as well as two parallel rows of yoga mats.

flight crew for approval. Other equipment for experiments was staged as needed after the airplane reached a safe altitude. Loose objects are a safety hazard during the flight because they can impact people during changing gravity conditions. Therefore, anything that needed to be held by Ambassadors was stowed in or on their flight suit, or in cabin storage to be handed to individuals as needed by support crew. All personnel on the aircraft were strapped into seats during takeoff and landing, and able to move into their designated experiment positions once altitude was reached. For Ambassadors with mobility disabilities, the first lunar-gravity parabola was used for support crew to assist in transfer operations from their seats to home positions.

2.3. Operational challenges and experiments

To plan the experiments performed on the flight, we started from the following question: *What challenges does a weightless environment present to disabled individuals and mixed-ability crews, and what technologies and operational strategies can we use to mitigate them?* We then identified a narrower set of questions that considered the needs of the specific ambassadors and disability types represented on the crew. Our framework for approaching experiments focused in three broad research categories: (i) Functional Environment, (ii) Navigation and Translation, and (iii) Communication. (i) Functional Environment experiments examined how the physical environment of the airplane could be modified to make it more functional and accessible, where the environment included both the plane cabin and flight suit. (ii) Navigation and translation experiments focused on limb movement, body translation, and station keeping (i.e., staying in place), as well as spatial awareness, orientation, and wayfinding. (iii) Communication experiments focused on direct communication between crew members, communication to crew via devices, and devices used for reading and writing. Within these research areas are several different Lines of Investigation, each of which contained one or more specific experiments (Table 1). Individual experiments are described in the following sections. Descriptions are organized by the disability groups which we recruited for the flight, starting with the specific questions relevant to each group and leading the experiments which developed from them.

Our general approach was to try the simplest and most analog solutions in each case as a first step towards refining what types of solutions and technologies show promise for future research. We also endeavored not to over-engineer solutions that were too specific to the Zero-G plane itself or the recurrence and duration of parabolas. While this is practically necessary to some extent, there are clearly differences between the experience of a Zero-G flight and the experience on a space station, another planetary body, or during inter-planetary cruise. We use the term experiment in this context to include both tests of a specific technology or tool, as well as tests performing defined actions or tasks. Zero-G flights are costly, limited in duration, and limited in the number of fliers. Further, the duration of an individual parabola is very short, limiting what can be accomplished in any given experiment. With this in mind, we elected in Flight AA1 to focus on the quantity rather than robustness. By performing as many experiments using as many types of technologies as we could, we could narrow down which types of solutions and devices were worth pursuing with more thoughtful and systematic experimentation during future flights. As a result, our findings for Flight AA1 experiments are somewhat qualitative. Nevertheless, they provide invaluable insight into how individuals with disabilities function in weightlessness and the challenges with respect to accessible design we need to overcome to progress in making human spaceflight more inclusive.

2.3.1. Mobility group

- How do Ambassadors safely leave and return to their home positions?
- How do Ambassadors with partial or full paralysis maintain limb control against inertial forces?
- How do Ambassadors with mobility disabilities station keep in microgravity?
- Can Ambassadors with prosthetics safely remove and replace them in microgravity?

Learning to navigate and translate in weightlessness is a universal challenge requiring practice to overcome, but individuals with mobility disabilities may have unique considerations relating to lack of control over limbs, limited reach, reduced grip strength (muscle atrophy), lack of limbs, or removal and stowage of prosthetics. Initiating translation requires very little force to achieve a movement speed that is slow enough to maintain control and anchor safely at the destination. However, the challenge comes in which direction movement is initiated and how much control the individual has over correcting or changing the trajectory. Movement may be more difficult for people with limited or very specific limb control due to either their ability to reach and/or use anchoring objects in the aircraft or because unintended movement of paralyzed limbs may impart unwanted inertial forces on their body which could change their trajectory. Depending on their conditions, it was also important for some Ambassadors to land in the right location and orientation while coming out of zero-g to prevent bodily discomfort or harm during the negative-g and regular-g periods between parabolas. Some conditions offer more challenges than others to repositioning the body as it lands, and there is little to no time as gravity conditions change. The experiments in this area included i) leaving the home position and returning at the end of the parabola, ii) point-to-point movement, iii) straps, handholds, and footholds, iv) rigid canes, v) flight suit modifications, vi) removing and replacement of prosthetics during weightlessness, and vii) a custom designed magnetic prosthetic.

Textile straps and handholds were attached to the walls throughout the cabin for Ambassadors to use for anchoring and translation, assisting in both enabling Ambassadors to leave and return to their home positions as well as enact specific point-to-point movements (Fig. 3). For the Ambassador using arm prosthetics, a network of tethers was created to better facilitate climbing and movement (Fig. 4). For Flight AA1, minimal straps were placed on the cabin floor due to airplane emergency safety requirements, but the cabin set up permitted more on the Aurelia flight. Rigid canes were carried by two Ambassadors (either attached to their suits or handed to them by a support crew member during the flight) to test their usefulness in reach and stabilization against cabin

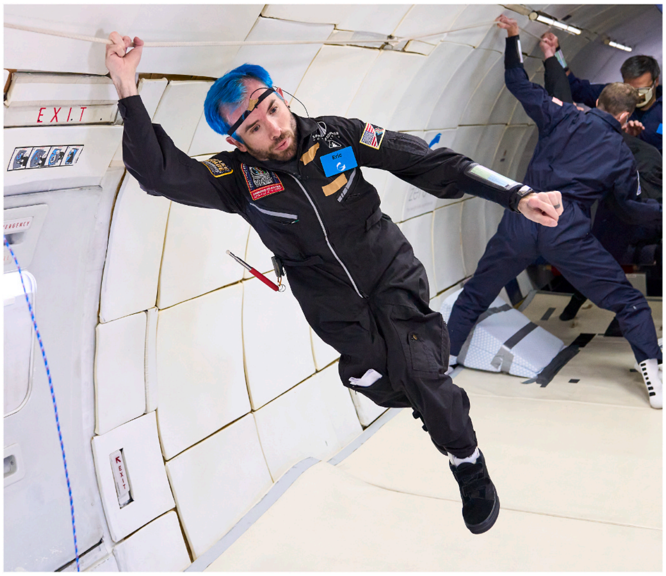

Fig. 3. Station Keeping and Inertial Forces
An Ambassador on Flight AA1 is floating in the air with one hand gripping a cable along the cabin wall. He has bright blue hair and a look of concentration on his face as he practices station keeping (i.e., staying in place) and moving along the wall, while testing how lack of movement in his lower limbs and with limited grip strength affects these operations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

walls. The canes were ~8 inches in length when contracted, telescoping out to ~30 inches.

The flight suit modifications were custom-tailored to each individual Ambassadors based on their unique needs. These were most relevant for the group with mobility disabilities to accommodate their limitations in range of motion, limb functionality, and their body shape. For example, modifications were made such as adding extra zippers to accommodate prosthetics, removal of excess fabric to fit body contours where atrophied or no limbs were present, adjustments to the placement of zippers due to restricted limb function, and adding pockets and/or ports to facilitate use of medical equipment. Two more broadly applicable suit modifications were leg straps and harnesses. Leg and ankle straps were added to the suits of Ambassadors with limb paralysis to dampen unwanted inertial movement and make manual adjustments of their limbs easier to accomplish. The Ambassador with prosthetic arms was fitted with a harness that was worn around their shoulders over their suit. The harness attached their prosthetics to their person, allowing for their safe removal, stowage, and replacement at will throughout the flight.

The Ambassadors using leg and arm prosthetics tested removing them during weightlessness during one parabola and replacing them, usually on the subsequent parabola (Fig. 5). In one experiment, a modular prosthetic leg with a magnet joint was developed to test the effectiveness of using magnets for assistive wearables, with implications for future applications including utility attachments and tools.

2.3.2. Deaf/HH group

- How do deaf Ambassadors receive critical communication from flight crew about changing conditions?
- Is communicating via American Sign Language (ASL) possible with different (e.g., upside down) or changing (e.g., tumbling) orientations?
- Does the act of signing impart momentum?

Communication is critical for any team in any space environment to operate effectively, and more importantly, safely. On a typical Zero-G flight, the flight attendants relay verbal updates from the pilot to the passengers to warn them of changing gravity conditions and when they can leave or should return to their home positions. This presented a challenge for our deaf Ambassadors, who needed an alternate method of receiving these messages. None of the flight attendants used sign language, and while there was an interpreter onboard in case of emergency, the goal was to explore solutions which ensure a deaf astronaut can interact and work independently. Of secondary importance is the ability to communicate non-emergency information between and among all hearing and non-hearing crew, which may include both work-related messages and socializing. The experiments for deaf Ambassadors in this area focused on i) testing viability of ASL during off-nominal orientation, ii) two different light beacons, and iii) haptic (vibration) devices for communication signaling.

The ASL tests during Flight AA1 were done at will between the two deaf Ambassadors rather than planned for a specific parabola, with the intent that they would try to communicate in any situation where they happened to be facing each other in off-nominal positions. An interpreter was present on the flight in case of emergency and for practical

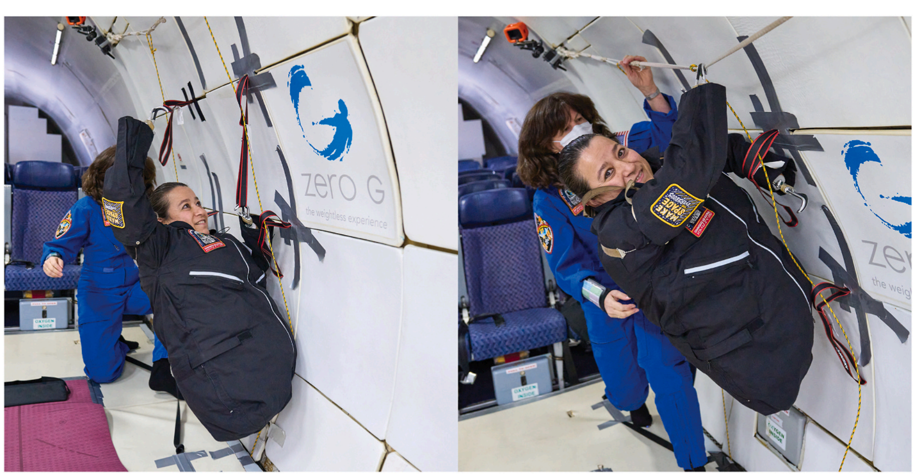

Fig. 4. Point-to-Point Mobility Test
Two snapshots in time show an Ambassador with prosthetic arms and no lower limbs climbing the cabin wall on Flight AA1. She is using the hooks on her prosthetics to grab handholds attached to the wall and propel herself upwards. She has a smile and look of confidence on her face. A support crew member is visible behind her waiting to assist if needed.

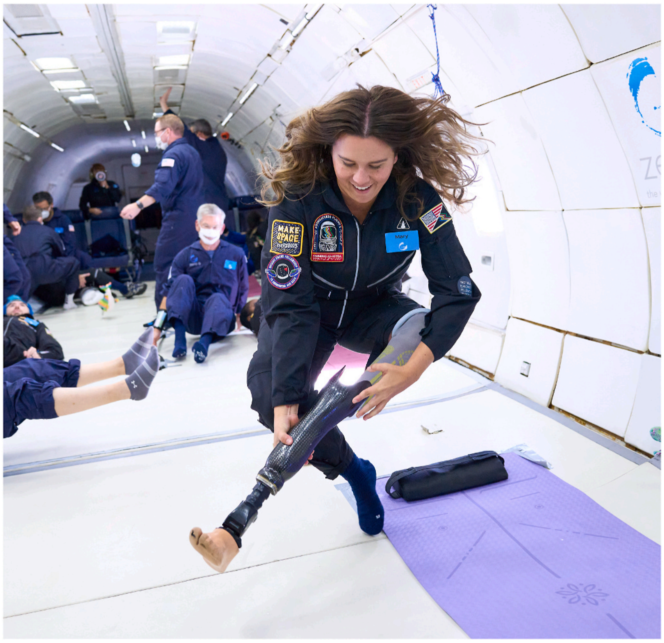

Fig. 5. Prosthesis Removal
An Ambassador on Flight AA1 is shown centered in the image using both hands to remove a prosthetic foot from her left leg. She is mostly floating with her other toe touching the floor. She has a big smile on her face and her long hair is floating gently around her head.

communication but did not participate in the tests. On the Aurelia flight, a more systematic test (Fig. 6) was done by two Ambassadors scripting a set of eight sentences which they communicated to the other, who then signed the same sentence in response to test their comprehension. Support crew assisted by orienting the Ambassadors in different pre-determined, off-nominal positions at the start of each parabola to enable as much time for signing as possible.

The light beacons and haptic signaling devices were used to communicate a change in gravity status going into and coming out of weightlessness during every parabola on Flight AA1. Both devices required a human operator. The light beacon was an off the shelf floodlight with color-changing capability which connected via Bluetooth to a smartphone. Two units were mounted to the floor where they met the wall, as mounting higher was not approved for safety concerns due to its weight, including the battery pack. The operator (a support crew member) flashed the light each time a change in gravity status was imminent using a different indicator color for going into and coming out of weightlessness. On the subsequent flights, a revised signaling system was tested which utilized rope lights in favor of the floodlight due to their lighter weight and larger line of sight. These were mounted along the ceiling and down the bulkhead (front wall of the aircraft) and were controlled via smartphone by a flight attendant in contact with the pilot.

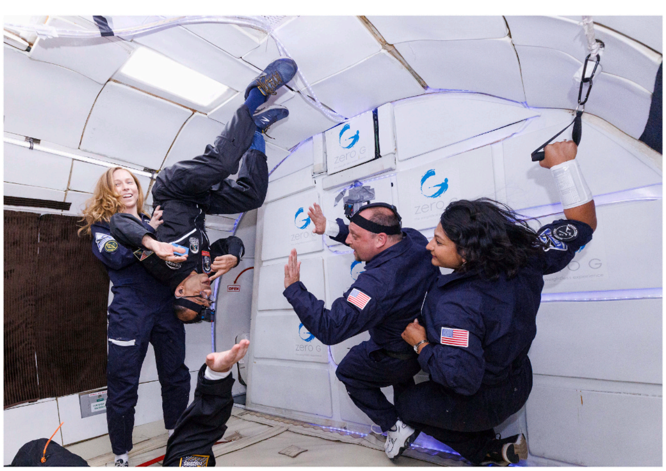

Fig. 6. ASL Tests
View of the aircraft cabin near the bulkhead on Aurelia, showing a green colored rope light snaking along the ceiling and down the wall. Centered are two pairs of individuals. On one side, a support crew member holds a deaf Ambassador in a sideways position while he signs to the interpreter standing upright across from him. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The haptic signaling devices we used were an off-the-shelf wearable and programmable metronome made by Soundbrenner (the Soundbrenner Pulse model). The Pulse is designed to be programmed with a set of custom, repeating rhythms that can be played and stopped as desired, and five devices can be controlled simultaneously from a single control device (a smartphone). Two distinct rhythmic patterns with varying intensity and vibrational style were programmed into the device, one which the operator used to indicate going into weightlessness and the other coming out. To facilitate swapping the devices quickly between Ambassadors partway through the flight, the devices were worn in a very small pocket on the upper arm of the flight suits rather than attached via wristbands. The haptic signaling devices were also tested by blind Ambassadors as a method of redundancy in case they had difficulty hearing the verbal status updates due to cabin noise.

2.3.3. Blind/LV group

- How do blind Ambassadors collect information to provide location awareness within the cabin?
- How do blind Ambassadors orient themselves for movement when their position is unknown?
- Does weightlessness impede the function or operation of basic tools used by blind individuals to read and write?

Blind and low-vision individuals use many techniques for orienting and navigating terrestrial environments which rely on gravity and may be disrupted in a weightless environment. Use of canes, for example, to probe their immediate surroundings, learn and practice spatial awareness of a particular or familiar setting, and identify the presence of both permanent and impermanent objects (new objects or objects in motion) around them becomes difficult when their orientation with respect to the floor is uncertain. Further, using a cane in a weightless environment is likely to impart momentum which results in unwanted motion and undermines its intended function. Auditory signals from known sources of sound can also be helpful for orientation in both new and familiar environments, such as sound beacons which play at crosswalks or the location of a piece of machinery within a room, as well as incident sound from, e.g., cars or people in the observer's vicinity. However, interpreting such signals while moving or tumbling in a weightless environment may be much more difficult or require more rapid processing and reflexes. Experiments in this area included i) rigid canes (same as for mobility group) to probe the environment, ii) sound beacons for locating home positions and distinguishing cabin walls, iii) a light source for distinguishing cabin walls, iv) tactile wall coverings for determining direction of motion, and v) two different haptic navigation devices.

The ability to determine the orientation of the body with respect to the cabin as well as direction of motion during movement are both aspects of spatial awareness required for blind and low-vision individuals to move around effectively in space. For orientation, both sound and light sensing are common strategies, depending on an individual's level of light perception. To create sound beacons we used off-the-shelf digital doorbells with a selection of distinct tones that could be set for each location. The Ambassadors would hold the buttons on their persons allowing them to chime the beacons at will. Two experiments were devised for these for AA1, though as we will describe in Section 3 they were not performed as intended. First, a beacon was to be placed on the floor at the home position of each Ambassador and used as a "homing beacon" at will by the Ambassadors. Second, two beacons were to be fixed to the cabin front wall and one side wall. In this case, a support crew member would chime them continuously and Ambassadors would test their ability to determine their direction of orientation in the cabin while in off-nominal positions. On AA1, yoga mats that highly contrasted the aircraft floor were used for Ambassadors with low vision as a passive test of to what extent their light perception aided in spatial awareness. On Aurelia, a dark colored fabric was used to cover one wall of the aircraft to provide a tactile marker (below), but also served to increase the area of the cabin providing contrast clues.

Both tactile and haptic devices were tested by blind and low vision Ambassadors to aid in moving around the cabin. On AA1, we tested two haptic navigation devices which used vibration signals to produce feedback to Ambassadors with respect to the location of obstacles. One device was designed by graduate students from the Massachusetts Institute of Technology Media Lab Space Exploration Initiative, who collaborated with AstroAccess on the first flight. By wearing it on the arm with an armband, it utilized the existing haptic feedback technology in a smartphone to signal the user. The smartphone communicated with a Bluetooth transponder which was fixed to the cabin wall, vibrating with increasing intensity with closer proximity. This device was used passively by an Ambassador while moving to and from their home location. We also tested a hand-held ultrasonic device made by Caretec, the Ray Electronic Mobility Aid for the Blind. This device emitted an ultrasonic beam in a straight line and used time-of-flight of the reflected signal determine proximity to an obstacle. This was used by the Ambassador to probe their surroundings while moving to and from their home location.

While the haptic navigation devices primarily served as aids for locating cabin surfaces, tactile markers were used for navigating along those surfaces. On Aurelia, two different tactile strategies were tested (Fig. 7). On one wall, a unidirectional fabric was affixed over a large, contiguous area. Like horsehair, this fabric feels smooth to the touch along one direction of motion, but has a rough texture in the opposite direction. The fabric was oriented such that, while touching the wall, smoothness would indicate to Ambassadors their hand was moving towards the floor, while roughness indicated movement towards the ceiling. On the other wall, strips of Velcro were affixed in parallel strips with nonlinear spacing, with closer spacing indicating proximity to the floor and wider spacing proximity to the ceiling. Utilizing the handholds for anchoring and translation or with assistance from support crew, the Ambassadors used the tactile markers to determine their orientation and which direction they were moving.

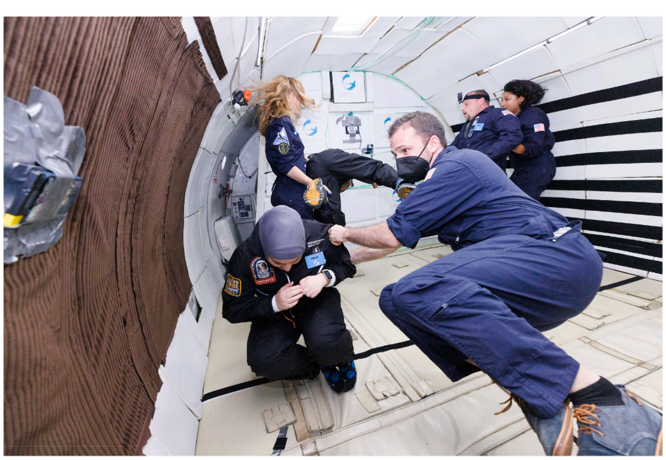

Fig. 7. Tactile Markers
On one side of the image, a dark color fabric is visible covering most of the wall and a flight attendant anchors a low vision Ambassador next to it. On the opposite wall, thick strips of Velcro are placed in parallel lines with decreasing spacing closer to the floor. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Communication via reading and writing is also a critical skill in space environments. Blind individuals use several tools to read materials and write in the performance of their jobs, in daily life, and for entertainment which an astronaut would also need to utilize while in space. The experiments for blind Ambassadors in this area focused on testing a i) refreshable braille display (or braille reader), ii) slate and stylus, and iii) a hands-free digital image enhancer. Braille readers are small, portable machines which produce braille writing via a set of pins which move up and down, and which can be read and scrolled through by the user (Fig. 8). A slate and stylus is a simple device consisting of a hinged piece of plastic that is solid on the back and contains a grid of holes on the front. A piece of paper can be placed between them, and the stylus used to make indents in the paper to write braille letters manually with even spacing. The hands-free digital enhancer is a device called the Think & Zoom consisting of a headband which reads EEG waves from the brain connected to either a smartphone, smart glasses, or a virtual reality headset (Fig. 8). The software interface interprets the EEG signal produced when thinking about a desired outcome and initiates the programmed response. In this case, an Ambassador with low vision used the headband to instruct a smartphone displaying text to zoom in, enhancing the text size to make it easier to read. Each of these communication technologies was tested at least once during the flight to ensure the lack of gravity did not interfere with their function and to observe any challenges in using them.

3. Experiment outcomes

Experiment outcomes and individual flight experiences were assessed by the team by reviewing video footage and photographs captured during the flight, as well as conducting post-flight interviews. In general, we found that most Ambassadors needed little physical intervention during the flight to ensure safety, though some was needed to aid in or recover during certain experiments. Zero-G flight attendants reported that their level of intervention was commensurate with non-disabled passengers and, based on their experience, seemed to be due primarily to lack of experience operating in weightlessness, not specific

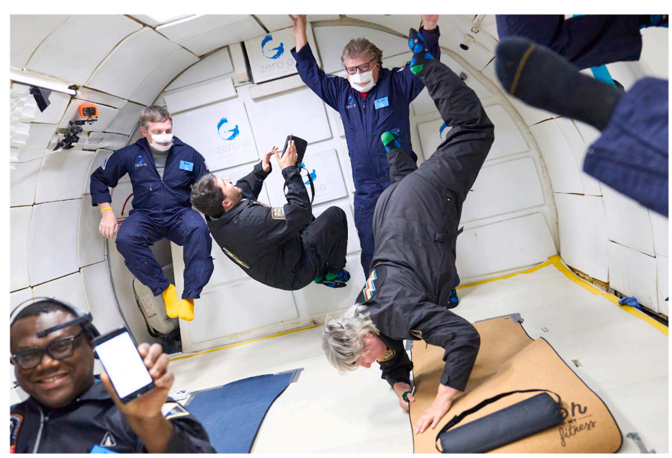

Fig. 8. Blind/LV Crew
Three Ambassadors floating in different orientations are seen in this crowded and dynamic image along with two support flyers. The Ambassador in the background talks to a support crew member while a braille reader in its case floats between his outstretched hands. To the right, another Ambassador is upside down holding an indistinguishable device while trying to anchor and reorient themselves using a yoga mat. A man's face is visible in the lower left as he holds up a smartphone to the camera which is connected to a headband he wears.

to their disabilities. Limitations and challenges due to specific disabilities or physical conditions was already somewhat mitigated by the fact that the experiments were designed for specific individuals, thus it is a positive result that their individual needs were correctly anticipated. This demonstrates that with thoughtful preparation and an accessible environment, disabled individuals can learn to operate in weightlessness with practice, as any individual would need. However, the needs of disabled individuals are extremely diverse and often nuanced, and the disabilities of our flight crews do not represent every type of disability. Additional research with more and differently disabled researchers performing more complex tasks, moving greater distances, using objects and equipment, and completing tasks as groups may help to identify where unanticipated challenges of weightlessness may lie.

The handholds and cables installed throughout the cabin were useful for all Ambassadors, who reported increasing confidence and dexterity in using them with practice as the flight proceeded. These had been installed somewhat ad hoc, based on expected need by individuals, however there was general agreement that more consistent spacing and placement would be easier to learn and more versatile, especially for blind/LV individuals who could benefit from exploring the cabin ahead of the flight. The deaf Ambassadors requested more footholds to use for anchoring because the use of both hands is required for them to sign. Predictably, the rigid canes were found to impart too much momentum to aid users in stabilization.

Most Ambassadors were regularly able to return independently to their yoga mats when coming out of weightlessness, including those with mobility restrictions and with low vision. Mobility restricted Ambassadors practiced point-to-point movements to explore whether their limitations offered any obstacles. Since their specific disabilities varied in nature, their experiences were somewhat unique to each other. However, all Ambassadors reported increased confidence and ease in moving with practice. Those with partial or no limb mobility reported that inertial forces influenced, but did not inhibit, the strategies they developed in moving and anchoring.

LV Ambassadors reported that if they did not move very far from their home positions, they could usually retain a general sense of spatial awareness, but also that tumbling action disrupted this and made it more challenging. Between the two Ambassadors with very low vision, one indicated that differences in light perception and/or color facing different directions in the cabin did help them to orient, but the other found that the rapidly changing light perception felt more disorienting and found navigation easier with closed eyes. The Ambassador who was fully blind experienced the most difficulty in maintain their sense of orientation. This suggests that individuals with any light perception use it in different ways, but more systematic and comparative research is needed to explore such effects further. This is a promising area for future research not just with implications for human spaceflight, but in understanding perception and spatial awareness generally. It is notable that, due to the number of people in the cabin, all Ambassadors were somewhat restricted in proximity to their yoga mats, and additional observations may be made on a future flight where greater distances may be traversed. On the other hand, the short duration of parabolas may limit what can be learned.

The flight suit modifications were reported successful by all Ambassadors, most notably the leg strap for those with full or partial paralysis and the prosthetic arm harness. Overall, there is not much we are able to report other than that they are critical to enable full functionality but unique to each disabled individual. Space suits for public and commercial crews are typically custom made for individual astronauts, however their initial design framework may or may not be well suited to specific types of modifications needed for disabled individuals. With only a small sample, we are not able to recommend any general best practices for flight suit design and modification. A better foundation for understanding accessible space suit design is key to facilitating more diverse astronauts. A detailed survey of the existing medical literature on the way that mobility disabilities restrict and modify movement in combination with a study of space suit design would be a valuable direction of research to pursue.

Ambassadors using prosthetics practiced removing and replacing them on alternating parabolas (Fig. 5). An Ambassador with a single prosthetic leg noted that they had to practice new techniques for removing it because without gravity they did not have the leverage usually provided by holding it down with their other foot. Simple devices attached to walls or floors and designed to be able to hook a prosthetic inside could provide such leverage to make the operation easier. Ability to stow them on their person was also universally deemed relevant. The strap-based harness for arm prosthetics worked well for this, but future studies could also explore Velcro and magnets. The prosthetic leg with the magnetic joint was found to be a successful proof of concept. Although the attachment portion did not have any specific use, future studies investigating which types of tools could be useful as worn on an arm or leg would be valuable. In addition, prosthetics which are hollow can be used for stowage.

On the first flight, deaf Ambassadors reported that communication via ASL was possible in various orientations and that the act of signing did not impart any noticeable angular momentum to the signer. However, they had practical difficulty testing because their hands were frequently in use for moving and station-keeping as they adjusted to how to operate in weightlessness. The more systematic test on the Aurelia flight better enabled signing comprehension tests by using support crew to orient and anchor the experimenters' bodies (Fig. 6). In this case, the experiment was performed by a disabled Ambassador and a nondisabled interpreter. They reported little difficulty in understanding and communicating to each other, including using signs which had very directional motions. They tested offset orientations in which they were still facing each other, enabling use of facial expressions, which are an important layer of inference in sign communication. Additional experiments where orientation obscured all or part of the face or hand motions would provide valuable insights in overcoming practical challenges in communication while performing activities. They also noted clearly feeling physical contact with the support crew holding them in place, suggesting it may possibly aid in the body's sense of proprioception and spatial awareness since the orientation of the crew member was fixed and known to them. An interesting difference observed between the experience of the deaf and hearing Ambassadors was that the latter frequently reported some amount of sensory overload due to the noise level in the cabin. On the other hand, one of the deaf Ambassadors described their experience as “serene”, suggesting they may have an advantage in their ability to concentrate and mentally process information in such settings over other disabled and non-disabled individuals.

The first version of the light beacons (the floodlights) had limited success for communicating change in gravity status because there were not enough in the cabin to ensure line of sight from off-nominal orientations. However, the version using rope lights (Fig. 6) was extremely effective, using a simple color change from blue to green when entering weightlessness, and back again when coming out. It had much greater line-of-sight visibility and provided more total ambient light to the cabin. All disabled and non-disabled crew reported it to be helpful in preparing for gravity change, showing great promise for the design of permanent systems for space environments. Ambassadors also reported that the haptic wristbands signaling gravity change are extremely promising as a technology because the feedback signal was clear regardless of orientation and they worked well for both deaf/HH and blind/LV individuals. Ambassadors did report that the devices would have been more effective if worn on the intended wristbands rather than in pockets. In future tests, we recommend that such devices be worn with a strap on some part of the body to ensure close contact to the skin at all times. One common issue with implementation of both the lights and the haptic signaling devices was the need for a human operator to transmit the signal at the appropriate time. The relay of information from the airplane pilot to flight attendants and then to device operators resulted in a significant signal delay which partly undermined its usefulness. On the Aurelia flight, this was improved by having the device operated by a flight attendant and thereby removing one relay step, however, advanced implementations could more easily mitigate this by automation technologies to reduce communication inefficiency.

The solutions explored by blind Ambassadors had limited success in overcoming obstacles but provided insightful outcomes. The sound beacons proved ultimately ineffectual due to the level of ambient noise present in the airplane cabin, which will be an issue in many space environments astronauts may operate in. Future tests could explore solutions using noise-cancelling technology, however this may also serve to limit useful ambient noise which blind individuals rely on to understand their surroundings. On the other hand, the Ambassadors noted that using other people in the cabin as sound markers also proved difficult because they had no way of knowing if either the person they were hearing or themselves were stationary or in motion.

The haptic navigation experiments also had limited success. Ambassadors found the wearable haptic proximity device to be too early in its development, citing that the communication to the transponder was too slow for real-time feedback. The handheld device was intuitive to use and responded very dynamically. However, Ambassadors noted that it was difficult to use largely due to the large number of obstacles around them (e.g., people, walls). If a proximity sensor is constantly triggering the information becomes less meaningful. Additionally, the single point source of the signal limits their applicability as passive proximity sensors because a device held, e.g., in hand may not warn the user if their legs are approaching an obstacle. However, they felt haptic navigation technology has some promise for active probing devices in very controlled contexts.

Ambassadors found the tactile wall markers tested on the Aurelia flight to be more successful overall and simpler to use than sound and haptic navigation devices. They reported ability to identify a specific wall of the cabin based on fabric texture or pattern, and direction along the wall (i.e., up or down) based on the spacing of markers. While limited to operations within reach of the user, this technology is a simple analog navigation solution applicable to any wall or surface that would enable navigation to and from locations in an environment. This is a promising area of research that can benefit from further innovation and testing on the ground before testing again in zero gravity. Ambassadors with some light perception also reported success in using high contrast wall or floor panels to help them identify the locations.

The braille devices posed no challenges to users and were found to operate normally in weightlessness. Since they are already at a mature level of development, braille readers could be incorporated into infrastructure alongside computer and display terminals. The hands-free image enhancer also functioned without issue. While still in an early stage of development, similar technologies have also been used to enable individuals with paralysis, missing limbs, or who have limited limb function or grip to perform a variety of actions on Earth [23] and could facilitate a diverse range of functionalities in space environments where use of the hands is critical for station keeping, moving, and performing tasks.

4. Discussion and directions for future research

In order for mixed ability crews to operate together, redundant methods of communication and navigation should be employed to ensure that all individuals can safely and effectively operate together and in the environment. Noise will be a significant challenge in most space environments. For example, the International Space Station is known to be quite noisy due to the presence of machinery and fans which make it habitable. Depending on their volume, locations, and the number of noise sources in a given locality, fixed sources of noise could serve to either aid or hinder individuals in wayfinding and orientation. Noise-cancelling technology can be tailored to specific environments and noise sources, allowing individuals to retain or filter specific sounds, however it also points to the need for non-sound based strategies for operating in space. Sign language can be learned by all individuals to enable communication with those who are deaf/HH, as well as anyone at distance or in locations where verbal communication (with or without audio headsets) is difficult. Research into how signing may be inhibited by space suits can provide crucial insights into how ASL and other sign languages may be used or adapted for space, and to provide inputs into accessible flight suit design. On the other hand, signing presents a challenge when one's hands are needed in performing a task or when individuals cannot be facing each other. One or both of these is likely in many situations performing the duties of an astronaut, and signing becomes even less reliable in an emergency when speed and/or need to perform an action may be of immediate and urgent importance. In this context, technological solutions which can help facilitate communication would provide redundancy. Haptic technologies also offer some limited application for active, person-to-person communication, for example using preset commands, responses, or signals that astronauts may trigger during routine tasks or emergencies. More complex solutions could explore voice-to-text capability which would enable more nuanced and longform communication, paired with display technologies using glasses, helmets, and screens.

Light and haptic technologies provide extremely promising areas of research to enable communication between astronauts and the environment, particularly in the area of safety. An integrated system using lights and haptics to communicate redundantly would be accessible to almost all disabled and nondisabled individuals, including those who are deaf, blind, and deaf-blind, as well as individuals who may become deaf or blind, for example in the case of equipment failure or injury. Lights can be spread throughout environments to offer good visibility, while haptics can be worn on most body parts. Such a system can provide critical safety signals to crews based on an active trigger by an individual or passively via instruments monitoring changes in environment (e.g., air pressure or oxygen sensors). Lights are already used commonly in buildings and crafts on Earth to denote pathways and exits for emergency egress, but in this context could also signal specific emergencies and/or procedures. Such systems should be designed with both color blindness and photosensitivity in mind, perhaps favoring symbolic panels which combine shapes and colors over flashing colors or patterns.

Haptic systems designed to communicate pre-set or emergency signals would be straightforward to integrate with a light system. However, more research is needed to apply haptic technologies to navigation and wayfinding. In our experiments, the crew found that haptic sensors for obstacle avoidance had limited applicability in small or crowded spaces but showed promise for navigation and wayfinding if innovations could overcome single signal sources. Systems using belts or vests that could provide 2 or 3D spatial information to users would be more versatile in weightless environments. Research and development on such systems in ground environments would be valuable and should place emphasis on clarity of spatial information and rapid response time between transponders. Medical research on the effects of continuous or long-term use of haptics may also be valuable, as the constant feeling of vibration could possibly lead to either decreased sensitivity or sensory overload. Wayfinding systems should be designed with both a passive mode, allowing users to either sense a continuous signal from a target source, and an active mode where they can "ping" a source at will. It is unclear whether systems incorporating both haptic communication (e.g, commands, alarms) and haptic navigation capabilities may be confusing or difficult to distinguish, and research in this intersection should explore whether it may undermine their safety features. Overall, haptics are a very versatile and promising technology for a wide range of space applications, but any permanent implementation in a space environment or integration with equipment will require careful thought with respect to the specific environment and tasks being performed. Analog solutions to wayfinding, such as tactile markers are more limited but do not come with risk of equipment malfunction and should be explored in parallel with more technological solutions.

In the broader context, all astronauts regardless of disability must train in order to learn to function in space. Most disabled individuals are already adept at innovating on strategies to perform daily functions in environments that are not accessible, and with practice are capable of performing tasks as well as any other given suitable accommodations. However, emergencies present situations which are not under ideal conditions. Practice cannot overcome poor design in every case and the stakes are high in an environment where humans are not already adapted to live. Universal operations (e.g., getting in and out of seats or suits) and emergency procedures (e.g., fire, depressurization, rescue operation) should be a major focus of research in designing both the physical habitats and tools astronauts will use, as well as their training. All procedures for space operations should be reviewed and practiced with diverse, mixed ability crews to identify what kinds of obstacles may come into play for differently disabled individuals and explore how different crew makeups may strengthen or weaken operational effectiveness. Equipment should also be assessed and re-designed for universal accessibility, such as face masks, door handles and latches, hand tools, and fire extinguishers. For example, a fire extinguisher needs to be operable by someone with limited grip or prosthetic, or by an individual with poor aim due to low vision. Modern technology and design innovation can meet these challenges if resources are devoted to it. Flight suits will be a major area of research in this context.

It is worth pointing out that, while our study and discussion has focused on individual and/or disability specific accommodations, future research into these areas will help to integrate these findings and solutions into a universally accessible design. There is a diverse range of types and combinations of disabilities present in the human population and the needs of specific individuals vary widely. It is impossible to design for every specific disability, if only because individuals with the same disability type still may live and function differently than each other. Individuals may also become disabled at any time in their life due to injury or trauma, and therefore people's life experience and lifestyles also contribute to this diversity. Therefore, it must be the longterm goal for environments here on Earth as well as in space, to be designed as universally as possible for the benefit of all people using it, including those who are nondisabled. This makes the development of universal aids (e.g., light beacons, haptics) that everyone might use, regardless of disability status, is equally as important as specific solutions that only one group would use (e.g., sound beacons for blind individuals). Some benefits of accessible design for nondisabled individuals are already apparent in modern infrastructure. For example, building and curb ramps installed for individuals using mobility aids also benefit those with strollers and luggage and are preferred over stairs by the majority of people [24], and audible announcements in airports and public transportation venues aid all hearing passengers, not just blind/low vision individuals. The real possibility of one day being able to visit or operate in space offers society, in this moment, the opportunity to be intentional about how we develop our narrative and physically build our relationship with it. With future research dedicated to progress in this area, and with the active participation by public and private entities who fund and control access to space, both Earth and the solar system can be made more inclusive to the benefit of all.

Declaration of competing interest

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

Acknowledgements

Mission AstroAccess is an initiative of SciAccess, Inc. and fiscally sponsored by SpaceKind. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Numerous public and private sector collaborators and partner organizations have contributed to AstroAccess's success, including the Whitesides Foundation, Aurelia Institute, Massachusetts Institute of Technology Media Lab Space Exploration Initiative, Massachusetts's Association for the Blind and Visually Impaired (MABVI), Space Frontier Foundation, Disabled American Veterans (DAV), Gallaudet University, San Francisco Lighthouse for the Blind, and American Institute of Aeronautics and Astronautics (AIAA1). A limited amount of this work was supported by the NASA Solar System Exploration Research Virtual Institute 2016 (SSERVI16) through the Project ESPRESSO node [80ARC0M0008]. All images in this paper are included with permission from "Zero-G/Al Powers" (AstroAccess Flight) and "Zero-G/Steve Boxall" (Aurelia Flight).

References

[1] D.L. Brucker, A.J. Houtenville, People with disabilities in the United States, Arch. Phys. Med. Rehabil. 96 (5) (2015) 771–774.
[2] M. Maroto, D. Pettinicchio, Disability, structural inequality, and work: the influence of occupational segregation on earnings for people with different disabilities, Res. Soc. Stratif. Mobil. 38 (2014) 76–92.
[3] R. Wells, S. Kommers, Graduate and professional education for students with disabilities: examining access to STEM, legal, and health fields in the United States, Int. J. Disabil. Dev. Educ. 69 (2) (2022) 672–686.
[4] L. Brown, Identity-first Language, Autistic self advocacy network, 2011, p. 4.
[5] M. Botha, J. Hanlon, G.L. Williams, Does language matter? Identity-first versus person-first language use in autism research: a response to Vivanti, J. Autism Dev. Disord. (2021) 1–9.
[6] Americans with Disabilities Act, 1990.
[7] P.R. Kofsky, G.M. Davis, R.J. Shephard, R.W. Jackson, G C, Keene, Field testing: assessment of physical fitness of disabled adults, Eur. J. Appl. Physiol. Occup. Physiol. 51 (1) (1983) 109–120.
[8] M. Bernardi, E. Guerra, B. Di Giacinto, A. Di Cesare, V. Castellano, Y. Bhambhani, Field evaluation of paralympic athletes in selected sports: implications for training, Med. Sci. Sports Exerc. 42 (6) (2010) 1200–1208.
[9] J.-P. Barfield, L.A. Malone, Performance test differences and paralympic team selection: pilot study of the United States national wheelchair rugby team, Int. J. Sports Sci. Coach. 7 (4) (2012) 715–720, https://doi.org/10.1260/1747-9541.7.4.715.
[10] S.C. Jeng, C.W. Chang, W.Y. Liu, Y.J. Hou, Y.H. Lin, Exercise training on skill-related physical fitness in adolescents with intellectual disability: a systematic review and meta-analysis, Disability and Health Journal 10 (2) (2017) 198–206.
[11] B. Clark, A. Graybiel, Human performance during adaptation to stress in the Pensacola slow rotation room, Aero. Med. 32 (1961) 93–106.
[12] R.S. Kellogg, R.S. Kennedy, A. Graybiel, Motion sickness symptomatology of labyrinthine defective and normal subjects during zero gravity maneuvers, Aero. Med. 36 (1965) 315.
[13] M. Heer, W.H. Paloski, Space motion sickness: incidence, etiology, and countermeasures, Auton. Neurosci. 129 (1–2) (2006) 77–79.
[14] P.A. Souvestre, C.K. Landrock, A.P. Blaber, Reducing incapacitating symptoms during space flight: is postural deficiency syndrome an applicable model? Hippokratia 12 (Suppl 1) (2008) 41.
[15] J. Everatt, B. Steffert, I. Smythe, An eye for the unusual: creative thinking in dyslexics, Dyslexia 5 (1) (1999) 28–46.
[16] N. Raz, E. Striem, G. Pundak, T. Orlov, E. Zohary, Superior serial memory in the blind: a case of cognitive compensatory adjustment, Curr. Biol. 17 (13) (2007) 1129–1133.
[17] K.L. Rush, W.E. Watts, J. Stanbury, Mobility adaptations of older adults: a secondary analysis, Clin. Nurs. Res. 20 (1) (2011) 81–100.
[18] W. Zhang, K. Radhakrishnan, Evidence on selection, optimization, and compensation strategies to optimize aging with multiple chronic conditions: a literature review, Geriatr. Nurs. 39 (5) (2018) 534–542.
[19] G.L. Albrecht, P.J. Devlieger, The disability paradox: high quality of life against all odds, Soc. Sci. Med. 48 (8) (1999) 977–988.
[20] T. Barskova, R. Oesterreich, Post-traumatic growth in people living with a serious medical condition and its relations to physical and mental health: a systematic review, Disabil. Rehabil. 31 (21) (2009) 1709–1733.
[21] V. Ramachandran, S. Dalal, R.A. Scheuring, J.A. Jones, Musculoskeletal injuries in astronauts: review of pre-flight, in-flight, post-flight, and extravehicular activity injuries, Current Pathobiology Reports 6 (2018) 149–158.
[22] N. Petersen, G. Lambrecht, J. Scott, N. Hirsch, M. Stokes, J. Mester, Postflight reconditioning for European astronauts–a case report of recovery after six months in space, Musculoskeletal Science and Practice 27 (2017) S23–S31.
[23] I. Lazarou, S. Nikolopoulos, P.C. Petrantonakis, I. Kompatsiaris, M. Tsolaki, EEG-based brain–computer interfaces for communication and rehabilitation of people with motor impairment: a novel approach of the 21 st Century, Front. Hum. Neurosci. 12 (14) (2018).
[24] H. Robert, Couch, Ramps not steps: a study of accessibility preferences, J. Rehabil. 58 (1) (1992). Highlights.