First Approximation of Population Distributions on the International Space Station

Justin St. P. Walsh*
Chapman University, Orange, California 92866
Rao Hamza Ali†
Anaheim, CA 92805
Alice C. Gorman‡
Flinders University, Adelaide, South Australia 5042, Australia
and
Amir Kanan Kashefi§
Adelaide, South Australia 5039, Australia

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This paper presents an analysis of data derived from thousands of publicly available photographs showing life on the International Space Station (ISS) between 2000 and 2020. Our analysis uses crew and locational information from the photographs' metadata to identify the distribution of different population groups—by gender, nationality, and space agency affiliation—across modules of the ISS, for the first time. Given the significance of the ISS as the most intensively inhabited space habitat to date, an international cooperative initiative involving 26 countries and five space agencies, and one of the most expensive building projects ever undertaken by humans, developing an understanding of which people are using different parts of the space station is critical for future usage of this and other stations. This study also sheds light on problems faced by future space station designers who are concerned with optimal usage of their habitats. The data from this investigation have been permanently deposited with Open Context. It is freely available for use under a Creative Commons license (CC BY 4.0) at https://doi.org/10.6078/M7668B9H.

I. Introduction

AS OF late 2020, the International Space Station (ISS, Fig. 1) had been continuously inhabited for more than 20 years. In that time, it was visited by more than 245 individuals from 19 countries and 10 space agencies. It is the longest- and most intensively occupied space habitat launched so far. In this study, we ask a simple question about its occupation: Who has been using the different parts of the space station? To put it more specifically, what are the distribution patterns of males and females, people of different nationalities, and members of different space agencies across the various modules of the ISS? These questions are highly relevant because space agencies and the commercial space industry are planning new stations and even more extensive missions (e.g., to Mars), with durations that go far beyond the average of 238 days served by the ISS's long-term crew.¶

Understanding which individuals are using which areas of any habitat, let alone a complex, multimodule habitat costing many tens of billions of dollars to build and maintain, is critically important for improving both future designs for architecture and work plans to be carried out by crew. Given the amount of attention paid by space agencies to the daily activities of their crew, these questions seem superficially like they should have straightforward answers. After all, astronauts are continually monitored by video in real time during their working hours (and possibly at other times as well), crew schedules are organized in increments as small as 5 minutes in the official ISS Operations Planner [1–3], and there are extensive public records of who was present on the space station at any moment. But no analysis of population distributions across ISS modules has been done, and, indeed, the raw data needed to perform such an analysis have never been generated from the existing evidence in agency archives. The evidence is, admittedly, difficult to identify and to work with. For example, crew work schedules are unreliable sources on their own, since they are subject to frequent changes: projects are rearranged due to unforeseen contingencies, crew are often interrupted during specified tasks, and sometimes they have to work in multiple locations simultaneously. These schedules also do not account for people's locations in periods outside of working hours.

Prior work in the discipline of human factors for space activity has largely ignored the question posed by this paper, even though multi-module space habitats can be said to have existed since the joined Command Module and Lunar Module transit phase of NASA's Apollo missions in the 1960s. Long-duration multimodule habitats emerged with the Soviet Union's Mir station in 1986, and two more such stations (ISS and China's Tiangong) have followed. With current work underway to develop several commercial stations for low Earth orbit (LEO), and the multi-agency Gateway station intended for orbit around the moon, all in the coming decade or so, it is increasingly important to not only establish a baseline understanding of how space stations are used and by whom, but to contextualize those results within the cultural, political, and social structures that condition them. Future space habitats will include people from a wider variety of backgrounds, including those who likely will not fit the category of professional "crew" tasked with maintaining a space station, but instead will be tourists, scientists, corporate researchers, and others. Already in 1996, Harris [4] noted the importance of flexibility in the macromanagement of multicultural space habitats, stating, "Mixed crews aloft (men and women, military and civilian, private sector and public service workers, diverse nationalities and cultures) will pose more complex management challenges and responses."

The state of human factors research during the design and operations phase of ISS habitation covered by this study is itself a significant feature of the cultural structures affecting life in space.

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*Professor of Art History, Archaeology, and Space Studies, Department of Art; jstpwalsh@chapman.edu (Corresponding Author).

†Independent Researcher.

‡Associate Professor, Archaeology and Space Studies, College of Humanities, Arts, and Social Sciences.

§Independent Researcher.

¶This average was calculated for the 113 crew members who served on ISS for more than 48 total days through Expedition 63 (mid-2020).

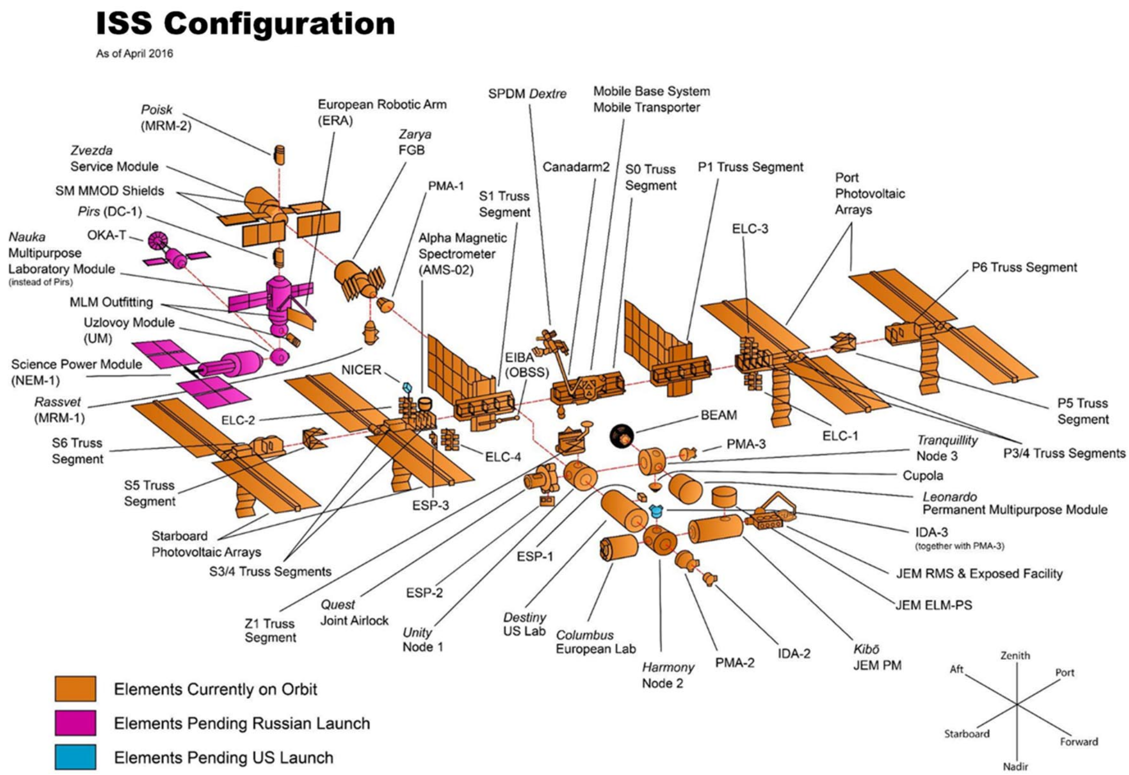

Fig. 1 Exploded view of the International Space Station, showing its constituent modules. (NASA, by permission.)

In 1995, NASA created a document called *STD 3000—Man-Systems Integration Standards*, to collect its understanding of all aspects of a spacecraft that related to human life, from safety to habitability [5]. This was superseded by *STD 3001—NASA Space Flight Human-Systems Standard* in 2011 (revised in 2015, 2019, and 2022) [6].[**] In both of these documents, ergonomics played a major role. "Access," however, is mentioned only with regard to physical reach (to controls, or to utilities like water sources or fire prevention systems) or with access to information through signage or computer systems. "Accessibility," a more complex concept combining opportunity, affordance, usability, and equity [7], is not mentioned at all. Work by scholars outside NASA has similarly tended to focus on ergonomics (e.g., [8]). Häuplik-Meusburger, e.g., concentrates on three themes (usability, livability, and flexibility) for architecture but does not discuss the use of all spaces by all crew [9]. While there is little evidence of explicit or implicit exclusion of certain crew members from any part of the ISS, the question of whether the crew members are, in fact, equally distributed around the station is what concerns us here.

II. Data

For this study, we collected occupation data and analyzed them for significant patterns [10]. Here, we report results from Phase 1 of this work, using the metadata associated with thousands of historic photographs as evidence, together with a list of crew members and their genders, nationalities, and agency affiliations. The photographs held by NASA represent its own imagery, as well as photographs from four of the five ISS partner agencies, the Japanese Aerospace Exploration Agency (JAXA), the European Space Agency (ESA), and the Canadian Space Agency (CSA). The Russian agency, the Roscosmos State Corporation for Space Activities (RSA), maintains its own photograph archive through its spacecraft contractor, PAO S. P. Korolev Rocket and Space Corporation Energia. We have so far been unable to access this archive (see Sec. IV.D for a discussion of the impact created by this lacuna).

Digital photography was adopted by the agencies from the beginning of the space station program, allowing for many more images of the ISS to be recorded than of previous space missions. By observing these images, we can identify the crew members and locations depicted in them. Work with the photographs has required several stages of development due to the large number of images, as well as the complexity of extracting usable data from them. The images analyzed in this paper were published by NASA's Public Affairs Office (PAO) on Flickr, the image-hosting website [11]. There are 8291 interior images from the first 63 mission increments, or "Expeditions," in the Flickr set, covering the years 2000–2020. NASA maintains a much larger set of unpublished ISS photographs for its own internal use. With the award of an Australian Research Council Discovery Program grant in 2019 (DP190102747), we were able to gain access to some of the larger photograph set; the results from analysis of that larger set will be the subject of a future paper.

III. Method

The International Space Station Archaeological Project has been working since 2015 to develop methods to observe and document the material culture of the ISS, the behaviors of its crew, and their associations with objects and particular locations within the space station [12]. Lacking the ability to travel to the ISS, we have relied on data such as historic photography made publicly available by space agencies. Initial testing using the Flickr photograph set showed that manual tagging of people, places, and items could take hours per photograph. At the same time, this approach was validated by a pilot study of items displayed on the aft wall of the Russian Zvezda module [13,14]. In that work, we were able to begin to define cultural associations of specific religious and secular items with groups of cosmonauts and a particular location. We documented 414 instances of 78 unique items (including Russian Orthodox painted icons and portraits of space heroes such as Yuri Gagarin) seen in 48 photographs dating between 2000 and 2014.

The work presented here relies not on the images themselves, but instead on key metadata about them. The images published by

**The titles of the documents themselves attest to NASA's slow progress toward achieving gender equity, a point whose relevance will become clearer in the discussion of our results below.

NASA on Flickr are all accompanied by natural text descriptions that typically mention which crew members appear in them, and the location or module in which they appear, e.g., "NASA astronauts Jessica Meir and Andrew Morgan, both Expedition 61 Flight Engineers, work on orbital plumbing tasks inside the Waste and Hygiene Compartment aboard the International Space Station's Tranquility module" (Fig. 2) [15]. We were able to capture the identities of the people and places in these images using the natural text descriptions. The extraction of relevant content was automated using the Flickr API and web scraping software developed by our team. This software identifies, saves, and processes information from the web. For this project, the scraper accesses the Flickr site, parses the content of each page, finds the data of interest (in the example above, "Jessica Meir," "Andrew Morgan," and "Tranquility"), and finally structures the data as needed (two Americans, two NASA crew, one woman and one man, in Node 3). The scraping also removed from consideration approximately 2000 Flickr images that were not labeled with any crew and/or any location. Images that did not actually show a crew member, even if one or more names were mentioned in the respective text descriptions (such as an image of an experiment that showed only the relevant equipment, but not the astronaut working on it), were also excluded. This process left usable metadata from 6262 images. Metadata scraping of their descriptions yielded 10,346 identifications of 217 people in 12 modules (of which modules one is Japanese, one is European, six are American, and four are Russian).

One might expect, given the length of occupation and the number of visitors, that these identifications would have become evenly distributed over time across the modules, whether by gender, nationality, or space agency affiliation, according to the proportions of each group in the overall population of ISS inhabitants and visitors. Such a distribution would represent the evolution of a distinct ISS society based on shared experiences in orbit as opposed to terrestrial identities. The analysis shows that this hypothesis is rejected for each of the three variables ($p < 0.001$), although the conclusions to be drawn from these results will necessarily be tentative, pending future research. This p value is for an analysis of variance (ANOVA) test carried out to check if the means of counts of astronauts per gender, nationality, and space agency affiliation are significantly different from each other. The null hypothesis suggests that groups can be considered as part of a larger set of population. For each affiliation, we get a p value < 0.001 and thus reject the null hypothesis for all cases. Figure 3 shows the distribution of the images by module; roughly 75% of the images show the U.S. Orbital Segment, while 25% show the Russian Orbital Segment.

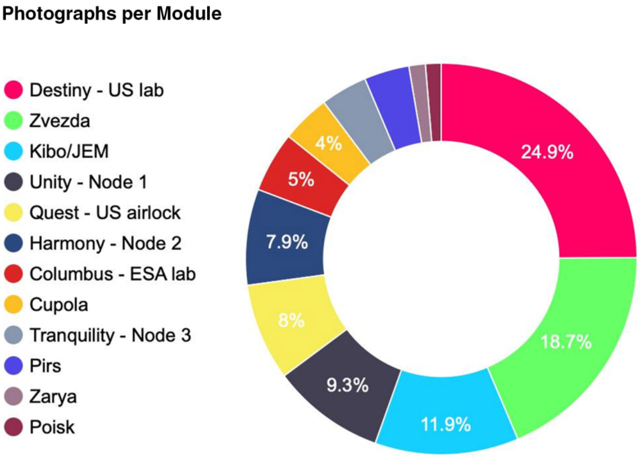

Fig. 3 Percentage of photographs published by NASA on its Flickr site by module shown.

IV. Analysis

A. Gender in ISS Modules

In the first 63 expeditions, 204 men and 38 women (84.3% vs 15.7%) visited the ISS. Of the women, 32 were American. In this period, Russia sent one female cosmonaut to the ISS, the same as Japan, Italy, France, Canada, and South Korea. In the slightly smaller subset of people captured in the Flickr images, males comprised 83.9% of the 217 people captured in the photographs, while females comprised 16.1%. The distribution of men and women in photographs of each module can be seen in Fig. 4. The bars in each graph are organized from top to bottom roughly from the front of the space station to the aft, with the U.S. Orbital Segment (consisting of the U.S., Japanese, and European modules) "ending" at the Cupola, and the Russian Orbital Segment "beginning" at Zarya [16–18]. For reference, the proportions for the two groups in the overall ISS population are seen in the bottom bar.

Low percentages of women were most noticeable in the Russian modules Pirs (1.9%), Zarya (4.0%), Zvezda (10.2%), and Poisk (10.3%). Only one female cosmonaut, Yelena Serova, who spent 167 days on the ISS in 2014–2015, was part of the crew during the analysis period; hence, the majority of this presence comes from other agency/national affiliations. Russia's antipathy toward women in space is well known [19,20]. Stuster's 2010 study of NASA crew diaries [21] suggests that cosmonauts expected female astronauts to undertake "really low-skill" tasks such as cleaning filters [22]. This

Fig. 2 A typical photograph published by NASA on its Flickr site, showing two crew members performing maintenance. (NASA, by permission.)

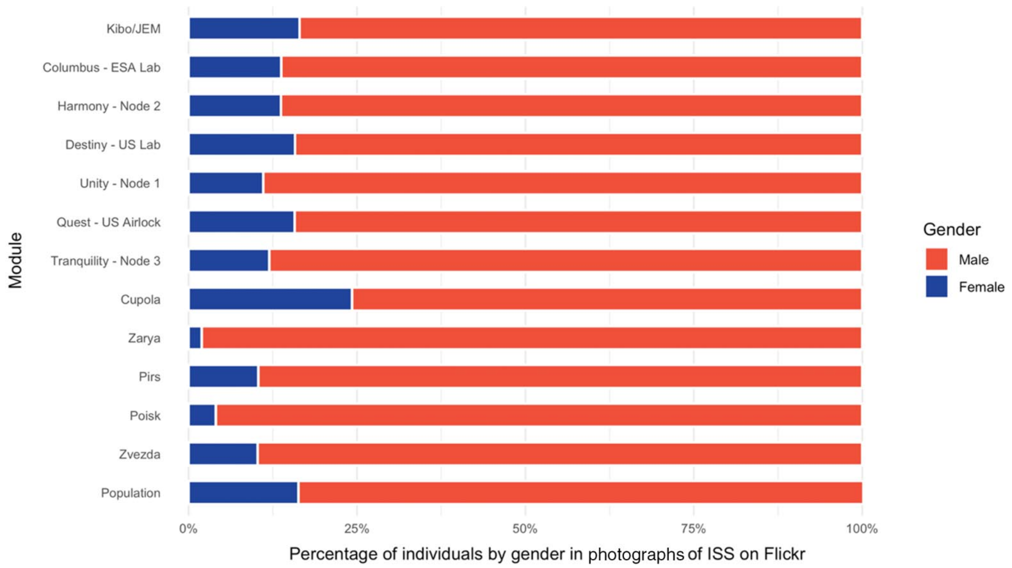

Fig. 4 Proportions of men and women pictured in photographs of ISS published by NASA on its Flickr page, organized by module.

preliminary data implies that, while equally physically accessible to all crew members, these modules may not be as socially accessible to all; however, it is difficult to separate this from the nationality of the crew (see below).

Other slightly low proportions of women were seen in Node 1 (11.1%), Node 3 (12.0%), Node 2 (13.7%), and the European laboratory Columbus (13.7%). Slightly higher proportions, close to the actual population, appeared in the Quest airlock (15.7%) and Destiny laboratory (15.8%). The only areas where women were seen in larger numbers than their proportion of the population would suggest are the Japanese laboratory module known as Kibo (16.5%) and the Cupola (24.3%). The extremely high proportion of women seen in Flickr images of the Cupola (where $n = 367$ individuals) seems worthy of note—the proportion of women in this location is 51% higher than it is in the general population. The Cupola is often featured as an aesthetically pleasing location for ISS images, one where work is not shown as often as leisure (Fig. 5). Astronauts are frequently seen simply viewing Earth through its windows.

The emphasis on women in this location in the Flickr photoset may reflect a choice—whether conscious or unconscious—by NASA's PAO to link beautiful images of Earth from space with femininity. By contrast, women are seen less frequently in spaces associated with rest, eating, and exercise, and slightly less frequently than expected in some spaces associated with scientific experimentation. Given the growth of concern about gender imbalance in the space industry globally, a finer-grained analysis of gendered experiences in the Cupola and other spaces seems likely to produce some useful insights.

Interestingly, the images taken in the Cupola bear some thematic resemblance to representations of women in visual art in the late 19th century and early 20th century, as documented by Dijkstra [23]. Paintings and sculptures exhibited in European galleries, and disseminated in prints to the general population, shared common suites of symbols capturing perceptions of femininity. Typically, these included female bodies in passive poses, appearing as if weightless, and in association with mirrors or circles. The persistence of these tropes into such a different 21st-century context bears further analysis, but may be just as potent in shaping representations of women in space.

The captions accompanying the photographs, however, do not show this bias in the choice of words used to describe images with female astronauts compared to those with their male counterparts. The *word2vec* algorithm [24], which uses a neural network model to learn word associations in large pieces of text, was used to create

Fig. 5 NASA astronaut Karen Nyberg looks out of the windows of the Cupola at Earth on November 4, 2013. (NASA, by permission.)

vector representations of all words and astronaut names present in the image captions. The vector representations were then visualized in a three-dimensional space. Two words in the word space are in close proximity if they are used in similar contexts in the image captions. The experiment was conducted to ascertain whether some action verbs or adjectives might have been used more commonly than others if a caption described a female astronaut. Figure 6 shows the three-dimensional space of words, with nodes representing male and female astronaut names colored in red and blue, respectively. All other words, excluding common phrases, used in the captions appear as gray nodes in the plot. We have determined that image captions share information regarding astronauts uniformly, given the cluster of astronaut names in the word space regardless of an astronaut's gender. This means that while visually there may be a conscious or unconscious choice in photographing and publishing images of female astronauts in the Cupola, the image captions do not describe female astronauts and their actions any differently from the male astronauts. This suggests that the captions are generated in a separate process from the selection of the photographs for publication.

B. Nationality in ISS Modules

ISS visitors and inhabitants from 17 countries appear in the Flickr image set (Fig. 7). Of these, Belgium, Brazil, Denmark, Spain, South Korea, Malaysia, Sweden, and the United Arab Emirates are each represented by one individual (0.5% each). There were also 3 Germans (1.4%), 4 Canadians (1.8%), 4 French (1.8%), 5 Italians (2.3%), 10 Japanese (4.6%), 46 Russians (21.2%), and 135 Americans (62.2%). Beginning with the largest group, on average, Americans made up 51.9% of the people seen in the photographs of each module. There were three locations where Americans were seen more often

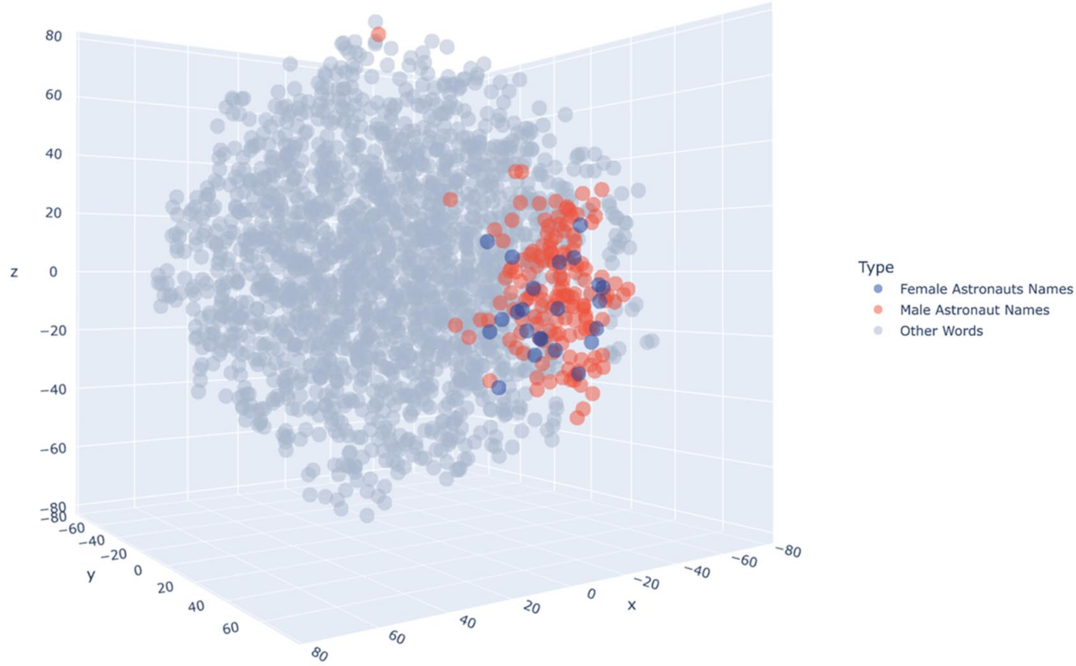

Fig. 6 A three-dimensional "bag-of-words" model representation of all words used in the captions of the Flickr photographs.

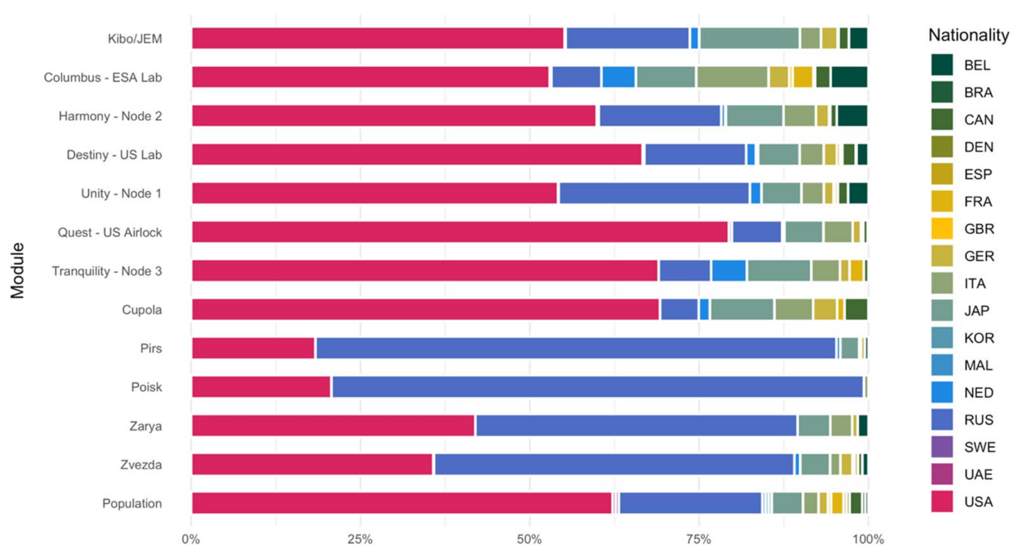

Fig. 7 Proportions of people of different nationalities pictured in photographs of the ISS published by NASA on its Flickr page, organized by module as in Fig. 4.

than their numbers alone would suggest: Node 3 (69.0%), the Cupola (69.2%), and the Quest airlock (79.4%). They only appeared in numbers roughly similar to their overall representation in Node 2 (59.2%) and the Destiny laboratory (66.7%). Slightly fewer Americans were seen in Node 1 (54.2%), Columbus (53.0%), and Kibo (55.1%); significantly fewer were seen in the Russian Orbital Segment: Zarya (41.9%), Zvezda (35.7%), Poisk (20.7%), and Pirs (18.3%)—the latter two are almost two standard deviations (SD = 19.3%) from the average. These results are almost reversed for the Russian contingent, who, on average, made up 30.4% of the people seen in a given module. More Russians were seen in Node 1 (28.2%), Zarya (47.6%), Zvezda (53.2%), Pirs (76.9%), and Poisk (78.6%). Russians appeared approximately in accordance with their overall proportion in Node 2 (18.1%) and Kibo (18.4%), while far fewer Russians were seen in Cupola (5.7%), Columbus (7.4%), Quest (7.4%), and Node 3 (7.8%). The fact that Americans were seen, on average, about 10% less frequently than would be expected from their actual proportion of the population, while Russians were seen 9% more frequently, may indicate a desire on the part of NASA PAO to show international cooperation with their primary partner in published imagery.

Japanese crew appeared in large numbers in Kibo (14.9%), the Cupola (9.5%), Node 3 (9.5%), and Columbus (8.9%). Notably, Pirs (2.8%) and Poisk (0%) were the only modules where Japanese astronauts did not appear in proportions at least equivalent to their actual population. This seems to indicate that Japanese crew members appear more frequently in photographs than other inhabitants of the ISS. Indeed, the number of images for long-term ISS inhabitants shows that, on average, Japanese crew members appear in 16% more published images per day than the average for all crew (0.51 compared to 0.44). Italians also make up a much larger proportion of the occupants of Columbus (10.7%) than their population would indicate; they also made up relatively large proportions of people seen in the Cupola (5.7%), Quest (4.3%), and Node 3 (4.2%). Italians were rarely seen in the Russian Orbital Segment, except for Zarya (3.2%). In total, Japanese crew make up almost three times as large a proportion of the inhabitants of Kibo as would be expected from their numbers; Italians make up 4.7 times the inhabitants of Columbus; and Russians make up more than 3.6 times the populations of Pirs and Poisk. These numbers indicate how, even in an ostensibly international space habitat, national linkages to specific spaces are still strongly apparent.

NASA astronaut Chris Cassidy recently discussed his loneliness during the time when he was the only American—and only resident of the U.S. Orbital Segment—on board, together with a pair of cosmonauts, during Expedition 63 [25]. Cassidy's description of isolation in one segment of the ISS is backed up by previously unpublished comments about privacy and personal space (although some quite positive) shared with us by Dr. Jack Stuster, who conducted the NASA-sponsored Journals Study from 2006 to 2010 and 2011 to 2016 [21,26]:

Comment: Another thing I feel slightly guilty about, but I do feel that I need some personal space. I'm still on video half the day, *and always in the JEM [Kibo] or COL [Columbus] or Airlock.*

Comment: Suddenly I'm really appreciating the solitude that I have here. It does help to have control of your own environment if you're going to be isolated. I'm trying to picture what it would be like up here with a crew of 6. It would be totally, completely, absolutely different. It would be more fun at times, and there would be more comraderie [*sic*]. That would be [*sic*] positive side. *On the other side, I would feel like I have my sleep station, but everything else is common ground. The entire U.S. segment is the equivalent of 'my house' right now.* So that would be [*sic*] huge difference.

Comment: *I must admit it is a little strange being the only one on the USOS side.* I will enjoy the tranquility but will be ready for company in a couple of weeks when X and Y arrive.

Comment: *X [Russian] decided he will stay in the USOS once the xx crew arrives.* Y [other Russian] wants to stay in the Russian segment. It took some convincing on X's part, but it is all set.

Comment: Other than stowage, all is fantastic. M [Russian] is in the best mood I have seen him since we arrived. *I think it is very nice for him to be alone in the Russian segment for the next two weeks.* That place is crowded with 3 folks. It is also nice down here in the U.S. side because we have half the people on ARED and T2 [exercise facilities]. Very casual and enjoyable at the moment.

These comments come from both phases of Stuster's study. The second comment emphasizes that some crew, at least, considered the public areas of the station to be "common ground," and that they felt that presence or absence in one of these spaces is not related to formal restrictions or personal discomfort. The small number of the journals studied ($n = 23$, or fewer than 10% of all visitors to the ISS), as well as the fact that they were all written by Americans, makes it difficult to draw conclusions about what people from under-represented or unrepresented groups might feel. The comments do seem to indicate that the tendencies of people to be in particular areas are related, especially to the externally designated work, eating, and sleeping divisions imposed by the various space agencies. The second-to-last crew comment appears to be "the exception that proves the rule," since apparently "it took some convincing" for a Russian crew member to decide it was appropriate to stay in the U.S. Segment (even though Americans had been staying in the Russian Segment for years before crew berths were added to Node 2).

It is possible to characterize modules as more or less "international" by reference to a statistical test known as Simpson's Diversity Index (SDI). This test was originally designed for ecology studies and measured habitat diversity as a function of the number of different species of animals present in a habitat as well as the number of individuals in each species [27]. It can be seen in Eq. (1), the formula for Simpson's Diversity Index:

$$\mathrm{SDI} = 1 - \frac{\Sigma n(n-1)}{N(N-1)} \tag{1}$$

In this equation, n is the number of individuals of each species, and N is the total number of individuals of all species. A habitat is considered maximally diverse (SDI = 1) when the number of individuals is evenly distributed across all species. On the ISS, this would mean that the population of a module is maximally diverse—i.e., if whatever nationalities were found in that module, each had the same number of people represented there. A low diversity score is found when one or more groups are represented by many more individuals than the other groups seen in the same module. In these terms, the ISS population as a whole showed only a middling diversity of 0.56, while the average module was slightly less diverse (0.53, with a standard deviation of 0.12). Columbus (0.69) and Kibo (0.64) were notably more diverse spaces (Fig. 8). These were followed by Node 1 (0.62), Node 2 (0.60), and Zarya (0.60)—an interesting result showing that geographic location within the station is not the only determining factor for diverse occupancy. It might be expected that the Cupola would attract occupants from all national groups—but in the Flickr images, at least, fewer than half of all nations are represented there, and the American population of this area is more than twice as large as all other countries combined. Again, this may reflect an effect created by the priorities of NASA's PAO to show their own crew in images selected for publication of this particular location. Pirs, Poisk, and Quest were the least diverse, and thus the least international spaces on ISS. These three spaces are where extravehicular activity is carried out —an activity that is particularly associated with Roscosmos and NASA, respectively, and which relies on their specific equipment, which is mutually incompatible. Russians rarely, if ever, receive training in the U.S. spacesuits and vice versa (although a few European and Japanese crew have received training in both).

C. Space Agency Affiliation in ISS Modules

Examination of space agency affiliations of individuals seen in various modules demonstrates, in *grosso modo*, similar patterns as the study of their nationalities (Fig. 9). There are two primary differences, however: first, the crew from nine countries all belong to ESA (18 individuals, 8.3%); second, four individuals in the photographs (1.8%) are private astronauts, better known as "spaceflight participants" or "space tourists," who do not belong to any space

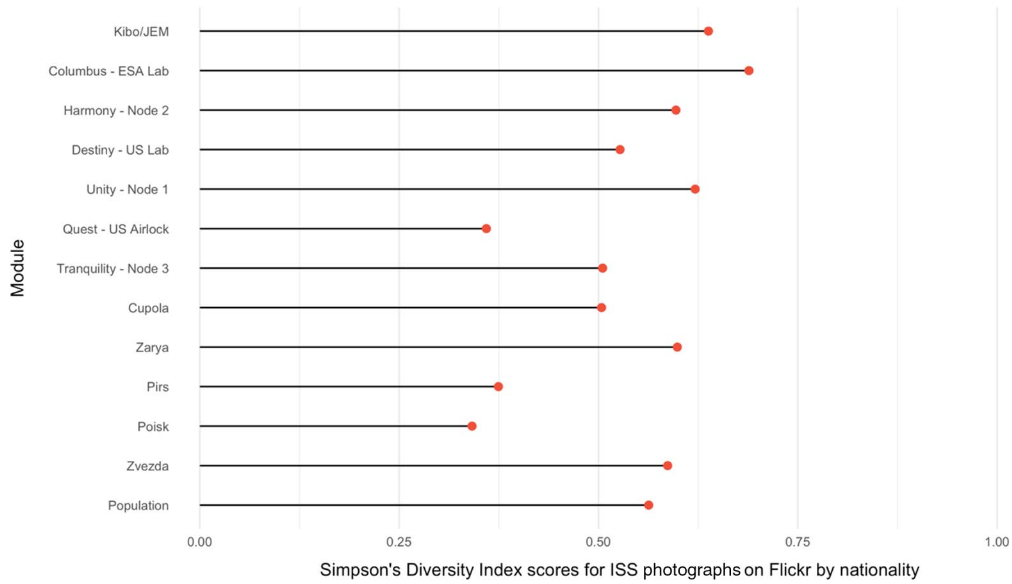

Fig. 8 Simpson's Diversity Index scores for ISS modules by nationality.

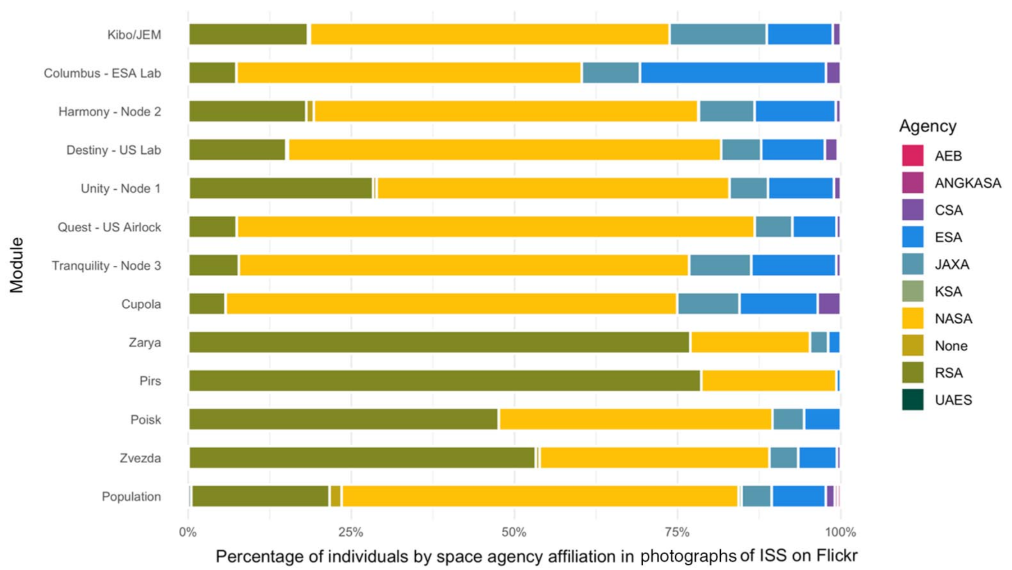

Fig. 9 Proportions of members of different space agencies pictured in photographs of the ISS published by NASA on its Flickr page, organized by module as in Fig. 4.

agency, but were included with their respective nations of citizenship in the previous analysis. Four more astronauts (0.5% each) are unique representatives of the space agencies of Brazil (AEB), Malaysia (ANGKASA), South Korea (KSA), and the United Arab Emirates (UAESA). As previously stated, the other international partner agencies that combine to run the ISS are NASA (135 individuals in this photograph set, 62.2%), Roscosmos (46 individuals, 21.2%), JAXA (10 individuals, 4.6%), and CSA (3 individuals, 1.4%). In this discussion, we will concentrate on the European contingent, since the other space agencies map almost directly onto the national distributions previously described. ESA crew made up a larger proportion of the crew seen in images than would be expected (average 9.7%, or roughly 17% higher than the actual population). This was especially true in the U.S. Orbital Segment modules, apart from Quest (6.8%). In Columbus, the European laboratory module, they made up 28.5% of the crew seen, more than triple the actual population. Node 3 (13.0%), Node 2 (12.5%), and the Cupola (12.0%) were also notably high. Private astronauts, on the other hand, make up only a very small percentage of the population of any USOS module, reaching 1% only in Node 2. This fact may be due to NASA's general disapproval of their presence on the ISS in the first decade of the station's use. It will be interesting to see whether private astronauts become more visible in published photographs since NASA opened up new opportunities for their visits in 2022.

With regard to module diversity according to space agency, as measured by Simpson's Diversity Index, the smaller number of groups containing the same total number of individuals yielded a more diverse distribution overall, although still not reaching high diversity levels of 0.8 or more (Fig. 10). The ISS population diversity was 0.58, with a module average of 0.52 and a standard deviation of 0.11. Most of the modules, including Kibo, Columbus, Node 2, Node 1, Zarya, and Zvezda, had SDI scores between 0.63 and 0.59. The U.S. Lab (0.52), Node 3 (0.49), and the Cupola (0.49) were lower than the ISS as a whole, and the three airlocks, Quest (0.36), Pirs (0.37), and Poisk (0.34), showed significantly lower diversity. The functions of the airlock spaces and their nationalistic natures have already been discussed above.

D. Biases in the Data

It is difficult to define with precision the difference between what is shown in the images and what the actual distribution of people across the station has been at any given moment. We note three identifiable

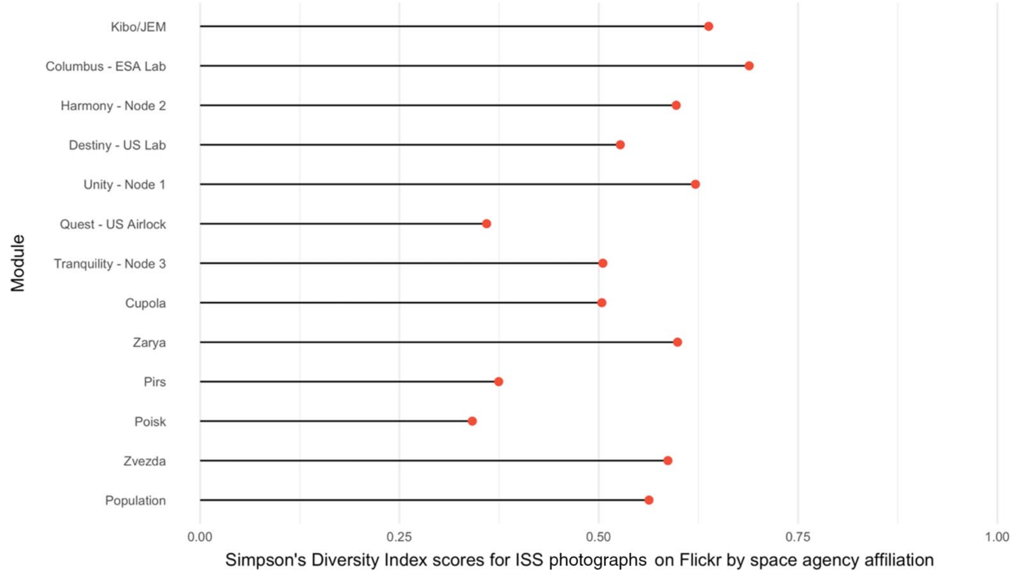

Fig. 10 Simpson's Diversity Index scores for ISS modules by space agency affiliation.

sources of bias in the set of photographs used for this study. First is the fact, already mentioned, that the Flickr images do not include images held in the archives of Roscosmos or its primary contractor, Energia. Such images have the potential to reveal different relative distributions of people, especially in the Russian Orbital Segment (ROS). We can say with certainty that the percentage of images in the Flickr set that show the ROS has declined precipitously over time, beginning already in 2001 (Fig. 11). Since 2008–2009, when NASA added its own crew berths to Harmony—Node 2, the percentage of published photographs showing the Russian part of the ISS has been greater than 20% only twice, and for 4 years in that period it was below 10%. We hope to gain access to the Russian images in the future to eliminate this source of bias, but the announcement in 2021 of new government rules governing the sharing of data about the Russian space industry with foreigners seems to make this an unlikely prospect.

One other area of bias related to the chronological distribution of the images is that the site was extended spatially over time as the station was built out and new modules were added. The ISS was not considered essentially complete until the addition of the Permanent Multipurpose Module, known as Leonardo, in March 2011. Leonardo is used almost exclusively for storage and was only shown in eight published photographs, so its results are not included here. Even now, more modules have been added or are expected to be in the coming years, such as the Russian Nauka (Science) module, which arrived in July 2021 and replaced Pirs. A somewhat mitigating factor to this bias is the small increase in the number of images in the last decade relative to earlier (2000–2010, average 312 pictures per year; 2011–2020, average 371 per year; Fig. 11), although the bulk of the photographs is clustered in the first half of that decade.

A final source of bias originates from the fact that the Flickr images were selected for publication from a larger set of unknown size that is maintained by one agency, NASA. The staff of NASA's PAO curates the Flickr images, according to the agency's priorities and interests, presumably focusing on the promotion of a positive public view of NASA and the ISS project. Indeed, one possible interpretation of the patterns identified above could be that, rather than demonstrating evidence of actual population distributions, we have instead only discovered that they reveal the curatorship of the images by NASA. We have already pointed out how the PAO's priorities might be visible in the ways women are shown in substantially greater numbers in the Cupola. At the same time, however, many aspects of the patterns clearly reflect outcomes that could be expected based on prior understandings of ISS political structures, such as the differences in populations between the U.S. and Russian Orbital Segments. We reiterate that this study, while revealing, is still only

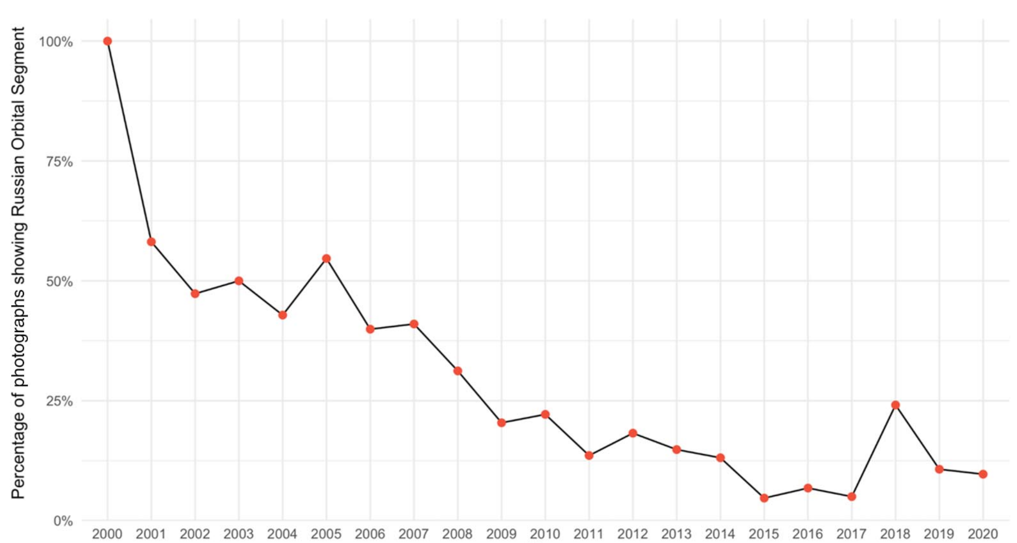

Fig. 11 Percentage of photographs appearing on NASA's Flickr site that show modules in the Russian Orbital Segment of the ISS, by year.

a first approximation of population distributions. Future work on the full set of images (now being made partially available to us) will help to illuminate the effect of this source of bias. Pending funding, the approval by the international partner agencies, and the consent of participating crew members, we also hope to implement a third phase of this study using a completely different data set: direct monitoring of individuals' movements around the station using astronaut-worn Radio Frequency Identification (RFID) tags. Each crew member will keep an anonymized tag on their person or in their clothing for a period of one or more weeks. As they move from module to module, the tags will be recorded by readers, allowing us to understand how much time different people spend in different locations. Comparing this systematic short-term study to the longer-term but more random data from the photographs should give a much clearer view of actual population distributions.

V. Conclusions

Even though our analysis is relatively basic—it can be encapsulated by the simple question, "Who was where on ISS?"—it is still unique: no space agency has ever been able to establish raw data for the presence of gendered, national, or agency groups living in an orbital habitat. These results begin to fulfill the promise of social science approaches to human interactions with the material culture of space. They demonstrate relevance to future mission planning and habitat design. Given the expense of maintaining orbital habitats, understanding the factors beyond engineering considerations and traditional human factors that structure the use of internal spaces has immediate application. For example, those modules or spaces that receive the highest traffic may also experience more "wear and tear," affecting the durability of internal infrastructure. We will gain an even better understanding of population distributions in the future by examining unpublished NASA photographs (and hopefully Russian ones, as well) and by integrating information about objects and activities into our study. Further machine learning analysis of other factors correlating with the categories used here may illuminate causes of the observed distributions other than agency, nationality, and gendered affiliations. It is worth noting that astronauts and cosmonauts do not work as domain specialists but are expected to carry out the whole gamut of required tasks, from various kinds of science to routine maintenance. We can therefore generally exclude specialization in one skill or another as a factor in the unbalanced distribution of crew around the ISS.

Even in this preliminary study, the analysis of people in the images seems to indicate the challenges of creating a space habitat whose population distribution truly reflects its internationalist ideals. The tendency of Russians to appear in their own modules, but not elsewhere, and the concomitant tendency of other groups (including women as a distinct class) to appear in the U.S., European, and Japanese modules, but not in the Russian ones, show that the space station may fairly be said to be divided down the middle at the Pressurized Mating Adapter that links Node 1 and Zarya. This fact is perhaps less surprising if we consider that the agreements that govern the ISS project for all practical purposes did, from the outset, divide responsibilities and jurisdictions for the station into two clearly delineated zones: the U.S. and Russian Orbital Segments [16–18]. For all that the ISS is a cooperative multi-agency project, it is well known that experiments—the primary work of the crew, other than constructing and maintaining the station—are not managed by a single joint oversight board, but instead by each individual agency according to its own priorities, and then placed on board as payloads via negotiation with the others. The crew members are therefore not a truly unified team, even though they do some training together before launch and work on some tasks together. Further, the various facilities on the station are explicitly labeled as having agency affiliations—as belonging to one or another nation or group of nations.

Our results reveal the alignments and tensions between individual behavior in the ISS modules, and the historical and political foundations of the space station's configuration. The reasons for divisions within a shared endeavor of multiple governments and international bodies in the recent geopolitical context—specifically, the development of the ISS in the aftermath of the Cold War, from what were originally separate planned U.S. and Russian space stations called *Freedom* and *Mir-2*, respectively—are relatively obvious and even understandable. But such political considerations do not mean that improvements are impossible. We can tentatively suggest that due to the way responsibilities, jurisdiction, and work have been divided on the ISS, the station likely falls short of optimal efficiency with regard to its human resources. Future studies may show that the imbalanced population distributions we have identified are actually detrimental to overall crew cohesiveness and morale. This issue should be considered a serious matter of concern for a mission that is one of the most expensive building projects ever undertaken by humanity. Indeed, habitat design for human factors—explicitly including sociocultural ones—must become a key research area for agency groups such as NASA's Human Research Program. Landon et al. state in their study *Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team* that "habitat design calls for adequate volume and layout supporting team activities (e.g., training, social time, community meals) and cohesion" [28,29]. Accessibility of spaces within a habitat should also become a consideration. New cooperative space habitat projects such as the NASA-ESA-JAXA-CSA Lunar Gateway orbital station and a proposed Russian and Chinese joint lunar base should consider how to create unified control structures, such as a single oversight board, composed of members from all participating groups, to determine what work will be done and develop architectures that are fully shared by crew regardless of their gender, national origin, or space agency affiliation. Similarly, commercial space station designers and operations planners will need to consider how to enable appropriate access to the various parts of their habitats, not only through architecture but also through effective management.

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A. P. Anderson
Associate Editor