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Astronaut Alexander Gerst aligns his posture with the dome while observing the sky above (Credit: NASA. Retrieved from: https://www.nasa.gov/content/astronaut-alexander-gerst-checks-out-station-cupola).

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The experience of movement in orbital space architecture: A narrative of weightlessness

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Abstract: Based upon a combination of architectural theories, the knowledge of space environment, and psychology of isolated and confined environments, this qualitative research aims to study orbital space settlement in a way to get the built space congenial to the human experience of movement. In this sense, sensors, self-propulsion or mechanical actuators, the inhabitant's mental and visual capacity for movement, as well as the represented and imbedded movement in the built environment—including pictorial representation, kinetic formation, and the movement of natural factors—are variables. So far, most of the studies on counter-measures for minimizing stress, which are stumbling blocks to the architectural promenade, have been based on pre-launch training focusing on professional training and selection of astronauts, planning for their in-flight challenges, and protecting them from dangers. Meanwhile, if we want to promote the experience of architecture in the outer space, narratives of movement need to be enriched, because not all occupants are professional astronauts. One way to study this matter is through analyzing movement in the built space and then synthesizing the results to gain an overview of a spatial montage in which motor planning for movement and route navigation have been facilitated. Narrative, in this sense, is a proper method to investigate this context of design. Therefore, analysis has been framed in the shape of a taxonomy

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Mosleh Ahmadi is an architecture scholar and researcher who received a B.Arch. and an M.Arch. from Islamic Azad University in 2015 and 2017. His previous published papers are mainly focused on architectural theory and designing including "The experience of movement in the built form and space: a framework for movement evaluation in architecture", and his main interest is study and research on interdisciplinary subjects of Architecture, Space Architecture, Neuroscience, and Environmental Psychology.

PUBLIC INTEREST STATEMENT

In the contemporary age, we have come to realize the limitations of living in our earth due to overpopulation, environmental crisis, and cosmic catastrophes. Just as how we learned to alter our homes from caves to high-tech mansions, we can change the context of our buildings from earthbound environment to the outer space. Because soon or later we would be forced to undertake this enterprise. Orbital Space Habitation has become a prevalent agenda in the current space exploration discussions. Before embarking on this venture, we need to have a better understanding of the interdisciplinary subject of orbital space architecture. One way to consider this interdisciplinarity is through the study of movement in weightlessness. In this sense, movement has been divided into seven major types. Through a precise investigation in the areas of Architecture, Neuromotor science, and Psychology of confined environments, a narrative of movement in weightlessness has shaped that benefits our understanding of space habitation.

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of movement in weightlessness. Through a qualitative investigation in Cupola Module, it has been thrown into relief that movement with regard to space has not been enriched as much as movement with regard to the form.

Subjects: Architecture; Architectural Design, Drawing and Presentation; Building Types; Interior Design; Visual Arts

Keywords: architecture; movement; space architecture; orbital space; weightlessness

1. Introduction

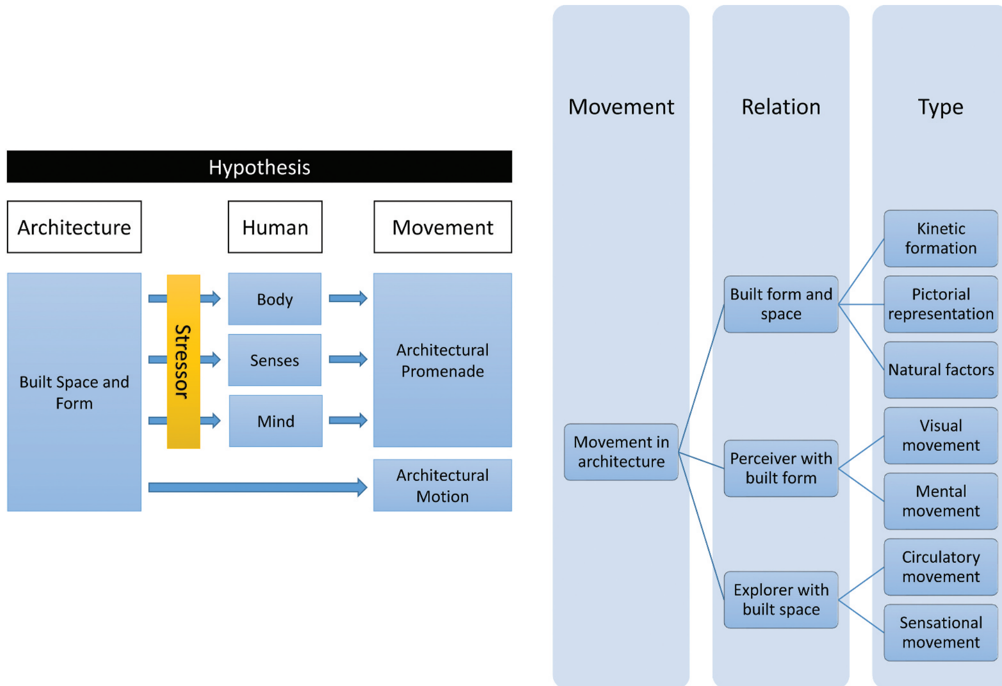
Movement is nothing but a fostered lack of balance. (Dubois, 1994)

The basic hypothesis for the experience of movement according to Ahmadi (2019) is that before any architectural promenade occurs, human needs to interact with the built space and form. This interaction later leads to stimulate three major types of movement (Figure 1) that are subdivisions of human interplay with form and built space. Three more types of movement exist regardless of human presence. All in all, establishing a proper system of movement with regard to those types, would cause a flourishing experience of movement in the built space.

Orbital Space Architecture is highly interconnected with "human factors, habitability, and behavioral health" (Harrison, 2010). Settling in space facilities with noble conditions would certainly bring about many challenges ranging from physical stresses (weightlessness, safety challenges, acceleration, and light-dark cycle), habitability stresses (noise, light and air quality, and vibration), psychological stresses (isolation, danger, monotony, and workload), and social stresses (privacy, and conflicts) (De la Torre, 2014) (Kanas & Manzey, 2008, p. 2) that impede our experience of movement in space settlement by creating stresses such as disorientation, motion sickness, visual illusions, and lack of privacy among many others. Behavioral health problems and stresses are similar to that of on earth referred to as sick environments: hot, crowd, noisy, smelly, and cramped environments (Harrison, 2010). The abovementioned stresses act upon the different types of movement that would be addressed in the following sections allocated to each type of movement.

Currently, most projects and research about space architecture are centered in the areas of robotics, energy, materials, and manufacture. However, the importance of movement in space architecture should not get fainted for it might cause instant or long-term issues related to improper designing for orbital space habitats. Movement in microgravity would significantly alter our experience of conventional movement experienced on earth. In outer space, the interaction between architecture and human is blocked and deteriorated by stresses induced by noble conditions, therefore unless countermeasures are employed to tackle those stresses, architectural promenade would not be generated. This results in a poor experience of movement. For reducing and eliminating stress/stressor in space habitats that lead to most known deconditioning factors namely boredom, monotony, isolation, forced socialization, homesick, and separation from nature, Kanas and Manzey (2008, p. 15) propose an adaptation to abnormal and extreme conditions in space. Furthermore, some exercises related to body posture and movement have been proposed to reduce the side effects of being exposed to microgravity (Dubois, 1994). In terms of architectural design, ergonomic built space and growth of living convenience—such as well-designed life appliances—can considerably lower the rate of stress. Hauplic-Meusburger (2011) in her book studies the built space according to five sub-activities of hygiene, work, leisure, sleep, and food. But is there a possibility for movement in architecture to alleviate these extremes and facilitate the process of adaptation whether psychological or physiological, by diminishing them only to cognitive adaptations of oneself? If there are, how? What would be discussed in this article is that through a logical argumentation and introducing a framework regarding the stresses/stressors of outer space, some principles based on the experience of movement for designing in weightlessness would be suggested.

Figure 1. Movement types in the built space of outer space (Adapted from Ahmadi, 2019).



For this essay, first and foremost, under an interpretivism system of inquiry and through an archival study across the existing materials—including books, articles, experiments, and anecdotal experiences of astronauts—a logical argumentation has been set. These arguments are articulated based on the previous discoveries and notions in the fields of architecture, space architecture, the psychology of confined environments, and microgravity studies. The seven types of movements (Figure 1) function as the underpinnings on which these arguments are made. Later, a taxonomy of the experience of movement in orbital space would be proposed that includes principle design strategies derived from those arguments. This taxonomy is used to shape a narrative of movement in weightlessness based on a video taken in the Cupola Module in ISS by NASA astronauts (NASA, 2016).

2. Circulatory movement in orbital space

Figure 2 shows Yves Klein's endeavor to grasp a notion of space in order to demonstrate it in his works of art (Goodbun et al., 2014). In a similar vein, to design for outer space, the designer needs to have an interpretation of the experience movement in microgravity. This matter is evident from the research of *Placing Space* by Eisenbach (2008): an attempt to comprehend "the construction of space from a movement point of view". Pieces of evidence for this necessity can also be observed from the useless, sometimes dangerous equipment and designing for space habitats. Namely, "metal triangular grid-work with shoes equipped with triangle plate (though triangular grid-work system proved to be useful), chair-type body restraints, and Fireman's pole" (Hauplik-Meusburger, 2011, p. 56). On the other hand, designing merely based on anecdotal experiences of astronauts and users (even research scientifically conducted on the matter of design for space) would draw the curtain over "projective competence" (Chow & Jonas, 2010), that eventually leads to an impaired imagination. Moreover, every movement is a sequence of postures generated by motor control. By considering this fact, Fairburn suggests a design based on "use and gesture" (Fairburn & Dominoni, 2015). For the time being, it is possible only through the study of an explorer and how he interacts with surrounding objects. Our erect and neutral postures, therefore, require different implications for circulation design (Figure 3).

Figure 2. Leap into the void (Photographed by Harry Shunk) (Source: http://www.yvesklein.com/en/oeuvres/view/643/leap-into-the-void/).

Circulation on earth is so trivial and insignificance due to the six million years of evolution that only providing appliances to facilitate this process has been taken into account in most of the research and projects. In contrast, circulation in microgravity requires much more attention because of its nobility, unfamiliarity, and the alternation it causes in the body's morphology. Our bodily movement in weightlessness is identical with the movement of planes in the air: Movement is no longer limited to forward-backward but it also includes pitch, yaw, and roll. In other words, while our locomotion on earth is restricted to the anatomical planes (sagittal, transversal, and coronal planes) relative to the verticality defined by gravity, our maneuver in microgravity is far more complicated, unconstrained, and accompanied by a freefall condition. Kneeling, standing, getting up, and leaning forward lose their meaning, followed by the furniture designed for these purposes. Whereas, motion on the third axis and rotation around the three principal axes will emerge. Furthermore, while on earth our movement is mainly dependent on lower body limbs, in

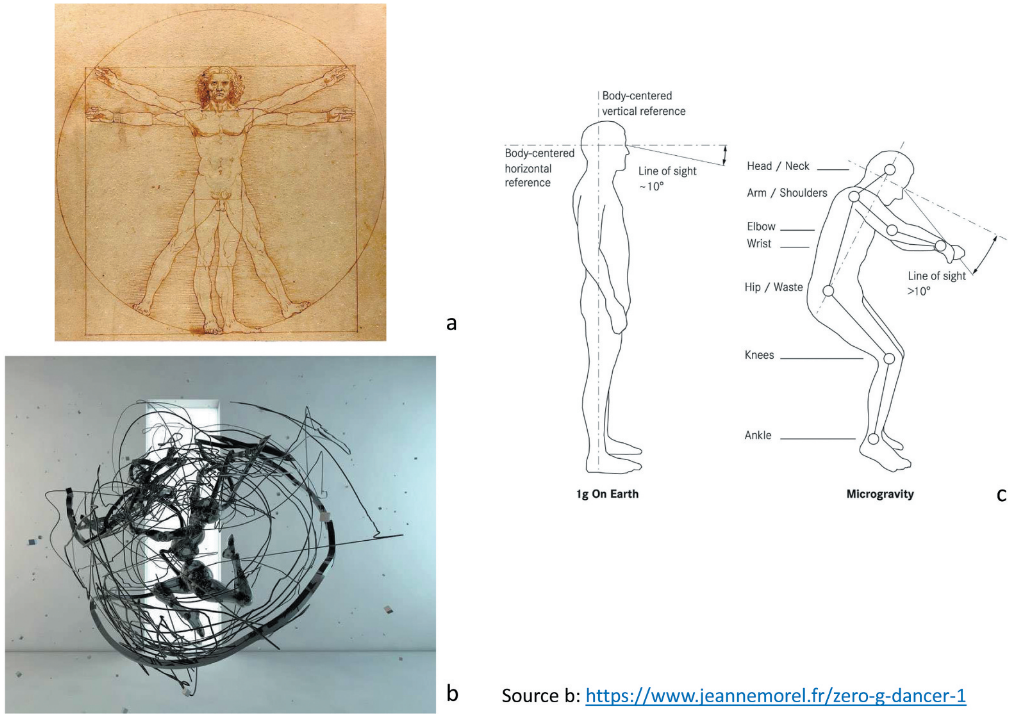


Figure 3. Erect posture in the presence of 1 g gravity as drawn by Da Vinci (a) (Source: Masali et al., 2011). Depicted segmental, torsional, and forward movement of body by dancer Jean Morel in the Synesthesia project (Illustrated by Paul Marlier) (b). Hauplik-Meusburger Subtly illustrates the differences (c) (Source: Hauplik-Meusburger, 2011, p. 19).

Source b: https://www.jeannemorel.fr/zero-g-dancer-1

microgravity movement is almost based on the upper body. So far as we tend to be almost “unaware of our feet” (Dubois, 1994). Dubois (1994) points out that a subject in space reacts to and plays with the environmental rhythm; so if we compare movement in space with dance, the place which architect designs, obviously plays the role of music. This requires architects to facilitate the body’s movement in the three-dimensional space along with other three rotational directions while helping the subjects to maintain tonicity of their muscles. In this sense, bodily movement which includes horizontal and vertical movements would also involve torsional movement (around somersault, and side somersault axes), as well as inter-segmental movement between segments of limbs and body.

As noted above, physical Motion in weightlessness is not constrained by the Cartesian system. Eventually, it ends up in disorientation. The prerequisite of circulation is navigation which, in turn, requires proper orientation. According to NASA-STD-3000 standards, orientation should be facilitated through visual cues, and work surfaces that define a “local vertical” (NASA, 1995). On the other hand, Doule (2014) posits that when individuals are no longer restricted to the ordering principals of earth, there is no need for horizontal floor nor other earthbound relics; It is “orbital mechanics” that defines them all. Meanwhile, another statement about the spatial orientation is based on the “ergonomic frame of reference” from which an explorer would subjectively perceive verticality (Kanas & Manzey, 2008, p. 58). They later express that to represent complex objects mentally, we need to align our verticality with theirs in an upright position (Kanas & Manzey, 2008, p. 60). Also, astronauts prefer to align their bodies with the local verticality of the habitat (Tafforin & Lambin, 1993). This elucidates us with this fact that complex forms not only help individuals to reduce the level of their stress related to space motion sickness[1] but also they provide people with orientation cues to simplify locomotion. However, knowing that postural and perceptual stability is made possible by holding handles and restrains after every spatial step (Mergner & Rosemeier, 1998), all the three abovementioned references namely local vertical, orbital mechanics, and ergonomic frame of reference should be considered simultaneously in the process of design.

It is suggested that problems of disorientation would be tackled with by devising Playscapes that employ "space of navigation" (Ackermann & Liappi, 2016) that leads to acquiring new skills of movement in space. Jane McGonigal in a video entitled *The Game that Can Give You 10 Extra Years of Life* (TED, 2012) has issued that how her traumatic brain injury symptoms disappeared after she tried to turn her situation into a game; Analogous symptoms to disorders that occur in space travel such as nausea, vertigo, and headaches attributed to motion sickness (Lackner, 2014). On the other hand, on earth, we as an evolved being who learned to explore its surroundings on foot, our circulation is restricted to our feet. However, in the absence of gravity, we are forced to bring our hands into play even more than our feet. Therefore, visual aids (e.g., texture and context distinctions, and color-coding) and mobility aids—foot and hand restrain—take the place of pavements, ramps, and stairs. For this purpose, "consistency" (Hauplik-Meusburger & Bannova, 2016, p. 119) in visual cues and mobility aids should be regarded to avoid confusion in circulation. On that account, relatively high control over "eye-hand coordination"—due to a combination of mobility and visual aids in circulation—is needed to perform almost all activities in microgravity (Kanas & Manzey, 2008, p. 48). However, architects should contrive a way to neglect this principle of circulation in space on account of the presence of disabled individuals. Hence, cognitive mapping of the built space should be facilitated by provisioning visual cues and localized mobility aids. A perfect element that provides both visual cue and mobility aid for circulation is the usage of Velcro on the floor surface (Hauplik-Meusburger, 2011, p. 252). Magnetic floor and shoes might be regarded as an alternative, too. All in all, the process of circulation in microgravity is acquisitive. It requires "new locomotion skills and new strategies of sensory-motor coordination" (Kanas & Manzey, 2008, p. 20).

Restricting the "slower pace of movement" in space (Bock et al., 2001) by designing narrower spaces, and defining surfaces might be an accomplished option for the status quo of space missions that are aimed to gain the maximum rate of performance. On the other hand, speaking about the experience of circulation leads us to the idea of completely tapping into the new possibilities of flying around large cylindrical or spherical spaces—especially when we learn the importance of "ample, and not occupied space" (Hauplik-Meusburger, 2011, p. 276). Hauplik-Meusburger and Bannova (2016, p. 27) enumerated "multiple access", "dual egress", "multiple circulation loops", and "vertical circulation" as the principal architectural elements of circulation in microgravity habitats.

Modern architecture has depleted our physical interaction with the built space. What if this trend of homogeneity becomes prevalent in space architecture? For example, ISS is described as a "homogenous and fairly sterile design" (Porter & Bradley, 2016). Getting benefit from our earth-bound interior design in an applied context can bring in the benefit of a mind freed of monotony or anxiety to prepare it for a mental movement. Salingaros (2017) proposes vernacular architecture as a solution for mental and physical disorders in the built space. However, to get utilization from this trend in the outer space, it needs to be rendered in an ultra-modern context. Plummer (2016, p. 25) in his book also sees eye to eye with Salingaros and explains how vernacular architecture offers numerous opportunities to get architectural experience enriched through the "benefit of exercise". Exercise in space is a challenge itself since there is no gravity. In addition, instruments designed for this purpose must not impose big forces from inhabitants on the habitat. Therefore, AREDs (advanced resistive exercise device) have been employed in a way that are not dependent on weight (Loehr et al., 2011). By adapting resistive, and flywheel exercises to the designs of mechanisms of transformation in the built space, architect opens doors for interaction with the built space in all directions.[2]

3. Kinetic formation

As depicted in Figure 1 (right diagram), at first glance, kineticism is regardless of the presence of the inhabitant. But every other movement (including kinetic formation) contributes to the experience of movement. On the other hand, the ambition of applying movement into buildings has long been practiced, among which "Revolving Buildings" (Ramzy & Fayed, 2011), "Plug-in-City, Blow-out

Village, Walking City, and Instant City" (Ching, 2011, p. 778) are prominent. Except for dynamic (revolving) buildings, these schemes did not work out, because to remain static, typical buildings on earth need to be designed statically. This is just in contrast with orbital space wherein buildings to remain static need to be designed dynamically. Hence, there is a marvelous opportunity for architects to satisfy their desire to express these movements in the form; Not only because of the required acceleration of any designed habitat but also for the artificial gravity that requires rotation. Current technologies propose space habitats the benefit of artificial gravity in two major forms: First by centrifugal force, and secondly through acceleration/deceleration. The former would be enabled via a round form rotating around its center and it is suitable for orbital habitats and habitats in "cruising stage without acceleration/deceleration" (Van Alebeek, 2014, p. 69). While in the latter gravity is induced by a habitat accelerated toward a destination or decelerated against it. To enumerate prominent orbital habitats in the previous works of architects we could count "O'Neill Cylinder, Bernal Sphere (that are two large-scale space cities) Stanford Torus" (Scharmen, 2018), "Tethered Artificial-gravity Vehicle, Electromagnetic Rotation System" (Hall, 2016), and "Growth-adapted Tensegrity Structure (GATS)" (Braddock, 2017).

Traditional Japanese architecture offers numerous alternations to the building's internal layout by the use of sliding walls referred to as "Shoji, and form-shifting machines" (Plummer, 2016, p. 73) to change the mood or for extension purposes. This quality of foldability and rotatability, which is addressed as "flexibility" (Hauplik-Meusburger, 2011, p. 103), should be put into practice in confined habitats to promote kineticism and thus to avoid monotony. Modern earthbound examples of kinetic formation are "Skin Unit Systems, Retractable Elements, and Biomechanical Systems" (Ramzy & Fayed, 2011) which can also be utilized for different purposes of limiting or permitting the natural light, and volumetric alternations in orbital space habitats. Similarly, "Deployability" (Leach, 2014, p. 102) is a necessary feature of future projections into space for a more facilitated transportation and arrangement. TransHab is an advanced habitat demonstrating inflatability (Hauplik-Meusburger & Bannova, 2016, p. 282). Maintenance, on the other side, allocates a big part of workload in current ISS space missions and EVAs. Kinetic formation by obviating the need for manual maintenance through a "Sensponsive architecture" (Oungrinis et al., 2013) can diminish stresses caused by workload, and qualify the relationship of man-machine.

4. Mental movement

The question of "what is happening?" in current space architecture has not been answered aesthetically. The only question inhabitants answer in their mind is related to workload that is almost influenced by stresses. Of course, function has priority in space architecture, not only for the mission success but also for the dangers which lay around the habitat. However, we should not become blissfully unaware of the dangers of an impeded mind from a mental maneuver stimulated by the form and architectural features. Coates has precisely cited this condition by stating that:

> 'Narrative in architecture can fulfill not only a psychological need but a functional need as well'. (Coates, 2012, p. 11)

Therefore, a "real-world theatrical set" (Lawson, 2005, p. 205) has to become dominant in the built space because we will realize that implications of this theatrical set in the confined environments are critical.

"Endless House" (Figure 4) idealized by Frederick Kiesler is an endeavor to conceptualize a design free of conventional floor, walls, and ceiling to provide a suitable generator of thoughts. These thoughts are embedded in the rooms with different features through which mind can wander. As mentioned in the first section (circulatory movement), our grasp of orientation is deteriorated in microgravity, and subsequently, the interior's conventional facets lose their meaning. This leads to a situation similar to what Kiesler tried to imply abstractly. Surprisingly, these shifts in thought would not be generated in the current modules of space habitats for they are extremely identical,

Figure 4. Interior views of the Endless House (Photographed by George Barrows) (Source: Springstubb, 2015).

and artificial. A remedy for this interruption is simply "variation" which ultimately makes room for "association, and perceived forces" (the two major types of mental movement) (Ahmadi, 2019) to be generated. Altogether, microgravity and variation promote the experience of mental movement from Endless to Boundless. Before explaining the subdivisions of association, and perceived forces that are "resemblance, meaning, inertia, imagined forces, visual forces, and dynamism" according to Ahmadi (2019), I start with Guided imagery as a type of therapeutic mental movement.

4.1. Guided imagery

Concentrating on the texture and color of an object, normally a natural object—referred to as "guided imagery" (WebMD Medical Reference, 2018)—is a behavioral technique, such as biofeedback, recommended for treating space motion sickness (Kanas & Manzey, 2008, p. 20). Natural objects synthetically designed as the interior form can be a good alternative to which the observer can redirect his mind from the motion sickness, as long as they don't interfere with the function of other systems. These synthetic natural objects not only are beneficial for treatment but also satisfy the intrinsic interest of humans for observing natural objects.

4.2. Association

"Reminiscence, and meaning", that are the two subdivisions of association (Ahmadi, 2019), play a vital role in breaking stresses for they remind us of the good earth. By describing a fruit sent to Mir space station as "a gift and aroma of the Earth" (Linenger, 2000, p. 97), Linenger implies that our senses can play a significant role in associating earth. therefore, sensory design should be highly regarded. Another example is stemmed from the preference of cosmonauts for even stimulated earthbound noises (Kanas & Manzey, 2008, p. 37). It points out the importance of pleasant stimuli for auditory sensory. Lack of this auditory input might cause hypersensitivity to the ambient noise. In this sense, any design should regard a pleasant background soundscape along with the aroma of that specific environment wafting through the place. This soundscape can also be accompanied by the attention-grabbing biophilic surfaces or "biological synthetic leaves" manifesting the natural objects (Van Alebeek, 2014, p. 49). Bader states that:

> Atmosphere is, in fact, the main constituent in the daily experience of a familiar built surrounding. (Bader, 2015)

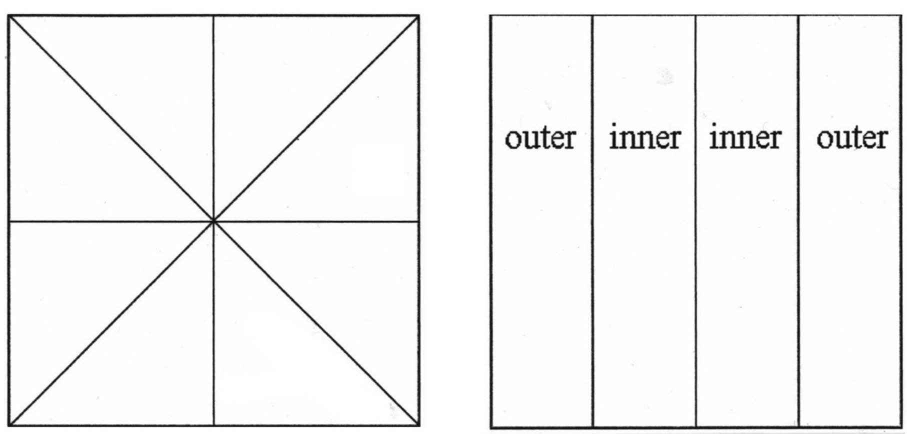
Therefore, an atmosphere that alludes to earth, is an attribute of a certain place that is self-generative not only in terms of events but also stimulated effects which help inhabitant to have a better experience of the place. Whether we like it or not, we are forced to utilize artificial materials for crafting space habitats. Also future methods, like in-situ resource utilization and 3D printing, offer the same level of artificiality. This high level of artificiality and confinement makes our mind incapable of distinguishing reality from imagination. Therefore, atmosphere becomes more critical for it creates an environment that prevents perceiver from being stuck in imagination due to Solipsism syndrome[3] (Scharmen, 2018).

4.3. Perceived forces

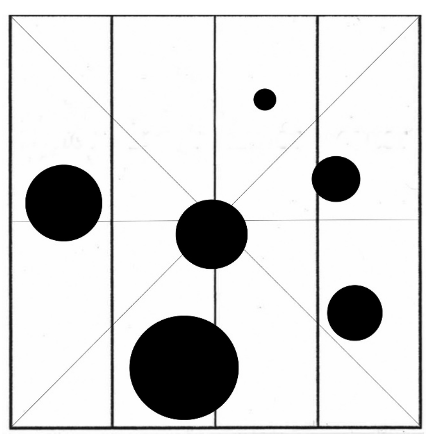
"Visual weight" (Arnheim, 2004, p. 23), and "visual inertia" (Ching, 2014, p. 35) explained by Arnheim and Ching would consequently lose their meanings in the absence of gravity. Two factors cause this: First, weight as a measure (as a visual cue in this case) is no longer available, and secondly, mass discrimination becomes impaired in microgravity (Kanas & Manzey, 2008, p. 57). However, gravity can be perceived in some particular forms to define the direction of ground (Figure 5). "Dynamic Spirit" (Hart, 1995) or "Dynamic Play" (Leach, 2014, p. 61) is a feature in buildings to give observers the illusion of floatation and rotation. To combat the mental stresses of weightlessness, designers have to reduce dynamism and have it forborne to some extent. We have used to observe objects in a painting or sculpture as if they have a visual gravity pull similar to the actual gravity on earth. These kinds of art can also play a role in inducing gravity mentally through manipulating attributions of spatial depth, location (e.g., distance from the center makes the object heavier and thus imply a direction for an artistic gravity), size, color, and knowledge about the context material (e.g., heavy or light materials). The abovementioned factors contribute to the "perceived gravity of the object" (Arnheim, 2004, pp. 23–26). However, to avoid visual oversaturation in space, the use of colors should be limited to medium brightness and saturation, with dark parts limited to small areas (NASA, 1995).

Figure 5. Eight measures of symmetry (a) (Wilson & Chatterjee, 2005). Example of an abstract composition (form) using circular objects (form components) with a dynamic balance implying a downward visual weight (b) (Source: author).

(a)



(b)



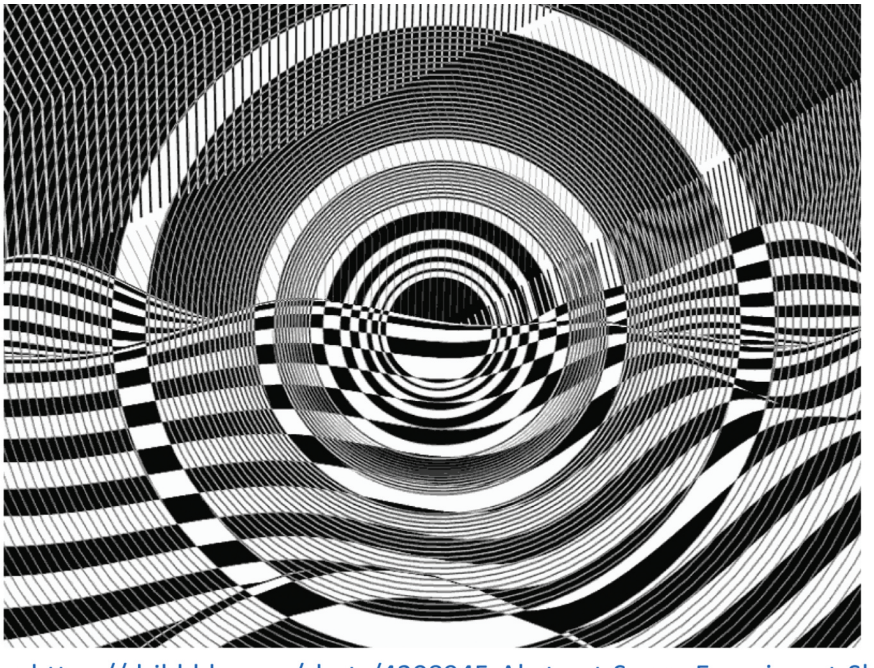
5. Visual movement

Gravity acts as an information source for perceiving objects' movement and orientation. Lack of this force induces "Visual Impairment due to Intracranial Pressure (VIIP), confusion in conceiving, and flattens the eyeball" (Paula et al., 2016). Thus, side effects of being in this new vision-threatening environment have been addressed whether as "illusion of objects displacement" (De la Torre, 2014), "blurring vision" (Paula et al., 2016) (as one rotates their head to observe), or "elevator illusion (visual mislocalization of targets as too high or low)" (Kanas & Manzey, 2008, p. 61). An induced visual weight is a corollary to the elevator illusion since "the greater the depth an area of the visual field reaches, the greater the weight it carries" (Arnheim, 2004, p. 24). Factors of movement concerning depth are "intensified perspective and multiple perspectives" (Ching, 2014, p. 44) from which architects have gained benefit to promote the experience of movement. However, regarding the prodigy of "elevator illusion", and the fact that in the same space an explorer would observe different perspectives (on account of the body's varied orientation) (Lebedev et al., 1990, p. 26), an architect should design sensitively. It is because there are already multiple and intensified perspectives even in simple forms.

Except for artificial gravity, architecture might not have any well-qualified response to optical illusions and discomforts which might even end up in irreversible vision problems (Crew, 2016). It is because these illusions require pharmacological and training solutions. There are some medical solutions like squeezing the eyeball via a band around it to bring the focus back in an eye with poor sight (Zandonella & Marks, 2002). An architectural countermeasure for the problem of illusions, in this sense, is related to accommodating the form in a way to provoke horizontal, vertical, rotational, and free movements of the eye. Meanwhile, the form must bring "attention" into play to provide a context for the eye to change the focal distance—thus, the curvature of the lens.

Similar to the illusion of displacement, Optical Art tried to manifest a sense of displacing and motion in the form (e.g., quadratura in baroque style) by applying "maximum contrast" (The Art Story, 2011) (Figure 6). A noticeable behavior of the eye is that our ocular muscles move downward and upward to seek verticality in microgravity for orientation purposes (Dubois, 1994) which is the so-called "visual scene polarity" (Reschke et al., 1998). Similarly, when our eyes encounter a scene,

Figure 6. Abstract experience of space inspired by Op art (Illustrated by Dağhan Kirişçi).[4]



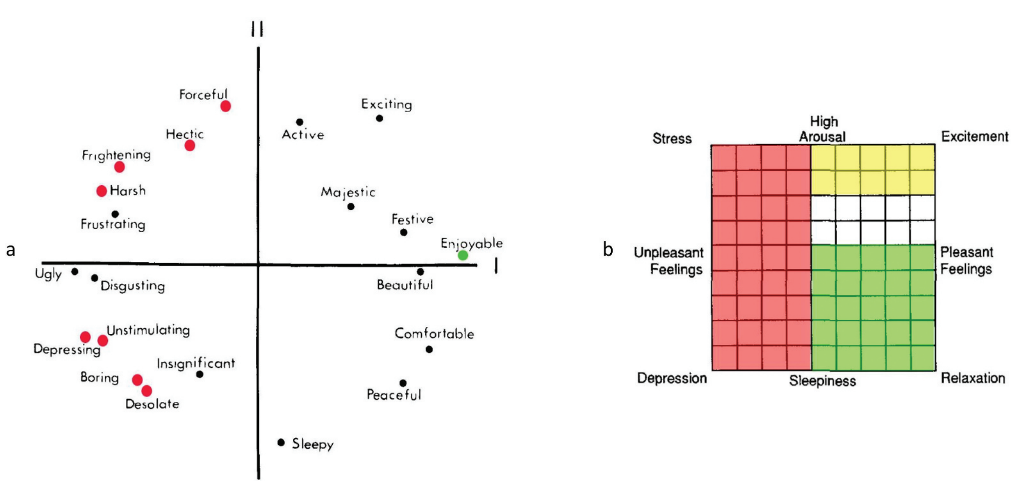
Source: https://dribbble.com/shots/4308945-Abstract-Space-Experiment-Shot08 like the one in the Op art, they become unstable, constantly moving, and change focus (Zanker et al., 2010). This could be responsible for the illusory motion. With this in mind, the illusion of displacement could be tackled by putting “spatial consistency” into operation—a term explained by Tilikete and Vighetto (2011). On the other hand, modules’ volume in space habitats is limited to cylindrical, spherical, and toroidal forms for two reasons: First due to “internal overpressure and efficiency” principals (Doule, 2014) in pneumatic structures, and secondly because curvilinear surfaces imply an ampler space (Porter & Bradley, 2016). This leads to a lack of conventional edges in buildings once our eyes used to move along them. This matter brings on some controversies which can be obviated by providing edgy and angular décor.

One of the most important facilities for visual movement is viewport. Almost in all related references, windows have been referred to as the most vital architectural element to reduce stresses. The role of visual movement through windows has been so emphasized that their application is recommended “as an aid to rotational adaptation” (Hauplik-Meusburger & Bannova, 2016, p. 148). Windows act also as a proper element for leisure besides diminishing the sensations of claustrophobia, separation from nature, and monotony (Kanas & Manzey, 2008, p. 166).

6. Sensory movement

In the Mars 500 experiment (ESA, 2011), scientists simulated a confined environment to examine the psychological problems associated with long-term habitation. In the end, they observed high rates of stress, and depression amongst the six participants. Anecdotal reports from astronauts show far more stress and depression rates in the wake of living in a much more limited space devoid of human sensory stimuli in microgravity (LBJS Center, 2016). With respect to the evidences, stress and depression are the two ambient mood variables that need to be avoided as much as possible in the first steps of the designing (Figure 7(b)) (more detailed negative adjectives are highlighted in red spots in Figure 7(a)). The quality of mood determines the quality of sensory movements afterward. Two factors regulate the inhabitants’ mood: “emotional balance/alertness, and feeling of sadness” (Kanas & Manzey, 2008, p. 39). In confined conditions, emotional balance deteriorates and would be affected by space-relevant stresses such as emotional tensions easily. Consequently, “Sensory Thoughts” (Pallasmaa, 2012, p. 45) which lead to sensory movements would be hindered. On the other hand, tendency, arousal, and time passing have been cited as the main factors of sensory movement (Ahmadi, 2019). Arousal has been referred to as the critical variable that regulates external and internal stresses leading to high performance, as long as it remains balanced at the optimum region (Kanas & Manzey, 2008, p. 52). In other words, the higher arousal is in earthbound

Figure 7. The clusters of adjectives describing the affective quality of place, adapted from Russel and Pratt (1980) (a). The red dots are the adjectives descriptive of the confined places in microgravity. The only green dot represents the enjoyability of residing in microgravity per se. The modified Affect Grid, adapted from Russel et al. (1989) (b). Red, yellow, white, and green areas represent detrimental, sensitive, neutral, and beneficial scales, respectively, for design in microgravity condition regarding mental health.



architecture, the higher the experience of movement is. But this movement needs to be fixated at a specific level in the space architecture to prevent stresses such as monotony—at lower levels of arousal—and anxiety at higher levels (Figure 7(b)). The sensation of time passing would be significantly alternated from that we sense on earth, which is no longer restricted to the 24-h day-night cycle. This altered sense boosts the sensitivity of time perception. For example, ISS represents 16 sunrises and sunsets relative to a day on earth (Williams, 2016). In another sense, this fact means that external time cues showcase a 90-min day. This condition is in contrast with our circadian rhythm and endogenous pacemaker; consequently, it brings about sleep disturbances. For this stress, seven countermeasures have been proposed (Wu et al., 2018) among which improved sleep environment and light treatment are the two factors that can be modified via architectural design. For example, the perception of time can be influenced artificially by a dome that virtually manifests the sky's condition on a big concave screen (Kolodziejczyk & Orzechowski, 2016).

One way, proposed by Oungrinis et al. (2013), is "Sensponsive Habitable Interior" which coordinates with changes in the endocrine system to create a comfortable environment and to remove sensory stressors by putting a combination of sensorial stimuli in place. Hudson (2015) defines an atmosphere as a combination of ambient sound, smell, touch, and visual attributes that have been employed to create such experience. To create an "atmospheric architecture"—a pre-conceptual sense of place—which benefits the user to enhance a pleasant experience of movement and navigation, Pallasmaa (2014) points out how atmospheric music, painting, sculpture, and film can endow the space with the ability to provoke a sixth sense in occupants. He refers to this as "faculty of grasping qualitative atmospheric entities" (Pallasmaa, 2014, p. 245). Among visual attributes which Hudson is referring to them are convex spaces, complexity, scaling coherence, perceptual fluency, and design patterns (e.g., fractals) (Salingaros, 2017). At first glance, complexity and perceptual fluency might seem to be in contrast, however they are initially complementary. For the former is essential to invoke soul and prevent monotonous sensorial movement, while the latter is critical to avoid confusion or disorientation. All in all, monotony in all aspects is a detrimental factor that needs to be dealt with at once. There are negative stresses in space notwithstanding, some other controversies justify the evidence for the existence of positive stresses that are originated from being in space. Levine posits that "the elimination of all stress is neither possible nor desirable" (Harrison et al., 1991, p. 309). In another point of view, confinement, weightlessness, and separation from society would lead to an increase in spirituality and bring about some positive changes such as the perception of the universe or spiritual change (Ihle et al., 2006).

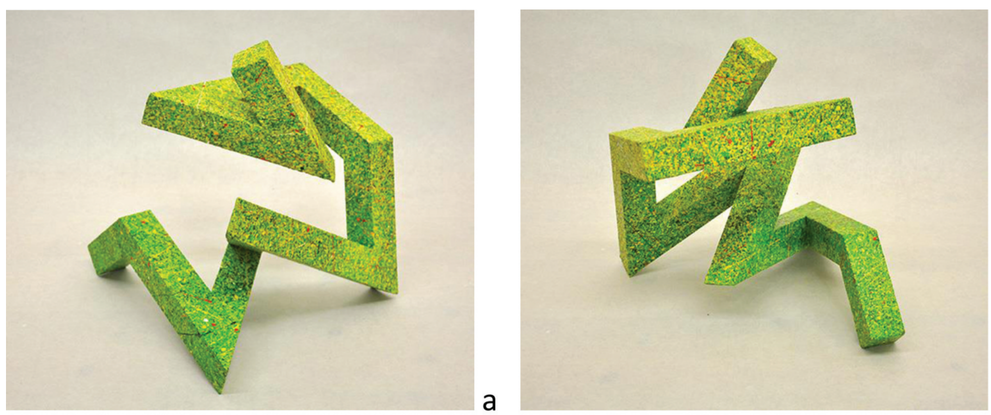
7. Natural contributors

Water, daylight, and airflow have been always natural key elements in architecture. Due to separation from nature in outer space, the movement of natural contributors is extremely restricted to just daylight; albeit, just indirectly through large periscopes equipped with special filters to prevent hazardous radiation from the sun (Porter & Bradley, 2016). In 1997, a large scale rotating ring was proposed by Bishop (1997) for space habitation. It was a megastructure big enough to hold an atmosphere in which a circadian rhythm similar to that of the earth would be created by giving a tilt to the ring's orbit. However, this scheme in this era is not practical. A more applicable scheme is "Tesla habitat" in which four concave mirrors are placed to direct the sunlight to the habitation areas and consequently provide external time cue from sun and day-night cycle (Misra, 2010). A countermeasure to tackle with closed-atmosphere environments is air movement. It is recommended that lighting and air supply should be provided overhead (Hauplik-Meusburger & Bannova, 2016, p. 156) in space habitats. In this way, the downward airflow and beam of light would provide inhabitants with a more sensorial cue for orientation, too. Furthermore, the circulation of fresh air is possible in the confined habitat by placing a greenhouse and a solarium, with the galley in-between.

8. Pictorial representation

If a built space exhibits a figurative portrayal of movement, it would be an inseparable component of a form which is so-called "pictorial representation" (Hardy, 2011). It effectively contributes to the experience of architecture through "sculpture, painting, and frozen transformation" (Ahmadi, 2019). Realistic paintings of landscapes are visually a better option for defining weight and the direction of gravity. On the other hand, abstract paintings that induce weight toward a direction by employing factors such as location and color (a composition of light and dark) could also be applicable. A proper way for inducing gravity might be Narrative Pictorial Representation. For instance, Sala dei Giganti depicts a story with all of its objects and characters that define a vertical ascension. In that room, one can follow the flow of actions ending to the ceiling by contemplating the drama from its beginning on the walls. Kinetic art such as sound wave sculpture and light sculpture not only can serve as an instrument to get the ambient stress (e.g., noise) and psychological stresses decreased, but also it improves the experience of movement in the environment per se. The idea of kinetic art should regard "simplicity", a countermeasure to reduce space motion sickness (NASA, 1995). We will come to agree that these abstract movements would become a critical element in long-duration settlements for they imitate the currents of nature. On the other hand, as Cohen and Hauplik-Meusburger (2015) imply, art can help future residents of space to deal with restrictions (Figure 8).

Figure 8. "Cosmic dancer"; first sculpture in space (Sculpted by Arthur Woods).



a b

Source: http://cosmicstones.org/cosmic_dancer_shop.php#

An option to improve healing in a hospital is a natural view (Salingaros, 2017). This natural view, besides observing our planet, can be created by Biophilic surfaces and greenhouses (Hauplik-Meusburger et al., 2014). It gains more importance since crewmembers are deprived of their essential need to communicate with natural elements. In another word, "surrogate views" (Hauplik-Meusburger, 2011, p. 227) which are alternatives for viewing "living and growing things" are other kinds of pictorial representation in confined and separated environments. "Simulated windows"—with artificial or synthetic views (Porter & Bradley, 2016)—even on a bigger scale, like simulated surfaces, can represent natural earthbound elements and currents. As a corollary, the built space transforms, and a connection to home would be established—mentioned as "reminiscence" earlier.

9. Discussion

To summarize the aforementioned notions and statements in a comprehensive form, a table has been drawn (Table 1) which depicts and categorizes the experience of movement in microgravity. Three major clusters have been derived under which different kinds of movements relative to them have been described. These types of movements are assigned a specific number which would be used in the following narrative.

Attached to International Space Station in 2010, Cupola Observational Module (Figure 10(b)) is somehow unique from the rest of the modules. What makes it more unique lies in a narrative of

Table 1. The table of movement clustering in orbital architecture (the numbering is used throughout the narrative to refer to these categories)

A. Movement of the Explorer (in relation to the built space)	**B. Movement of the Perceiver (in relation to the form)**	**C. Movement regardless of the Inhabitant (in relation to the built form and space)**
Circulatory Movement	*Mental Movement*	C1. Kinetic Formation: This notion accounts for all kinetic parts of the habitat which exhibit observable movement. It is divided to four major kinds of Skin unit system, Retractable element, Revolving form, Biomechanical, and Deployable parts.
A1. Bodily Movement: A proper grammar of movement is defined by a “General State of Tentativeness” with a spatial montage to zone the habitat into indoor and outdoor (difference in lighting, temperature, dimensions etc.) in order to generate “Sense of interiority” (Liddicoat,	B1. Association: A form resembles something linked back to our memory such as creating a ‘Sense of Home (Earth)’ as well as a personized space: An atmospheric design which associates to earth in all sensory aspects. On the side of the coin, association leads to meaning.	
A2. Projected Bodily Movement: Imagined movement of body through space (Hardy,	B2. Perceived Forces: A perceiver distinguishes patterns of movement in form/s such as Dynamism, Visual Forces, Imagined Forces, and Perceived Gravity.	C2. Natural Contributors: Light, Air flow, and Water in the built space.
	B3. Guided Imagery: Uniqueness and contrast (in terms of meaning) with the whole in some parts of the form facilitates guided imagery.	C3. Pictorial Representation: Painting, Sculpture, Frozen Transformation, and Virtual Reality which manifest some sort of represented movement.
Sensory Movement	*Visual Movement*	
A3. Time Passing: Mimicking the pattern of natural light on earth in the built space helps to enhance sleep quality and thus creating an atmosphere. The lighting design of the space can be provisioned as an ever-changing palette of colors and different hues to complement a day-night cycle and to provide visual cues.	B4. Optical Movement: Horizontal, vertical, and free movement of eye across forms and through spaces	
A4. Tendency: Any kind of spatial montage which is inviting for the explorer, generates tendency. “Haptic Design”, “Scent-sational Navigation”, and “Sonic Orientation” in a way that both facilitates route navigation, and makes room for a flexible architecture to attract curiosity and contemplation in motor planning.	B5. Marginal Attention: Referred to as ‘experiential edge’ (Bader,	
A5. (Aesthetic) Appraisal: Emotional or affective response to the embedded stimuli.		

movement through its space. In fact, before entering the Tranquility node, most parts of the form do not offer much for movement except the blue foot and hand restraints, as well as a set of equipment (e.g., electronic devices) disorderly opposed to the anaemic surfaces. This collection of synthetic view depletes everybody from a rich experience of movement. However, upon our presence in the Tranquility node, a pale blue light in front of us attracts attention (B5) which creates a unique place defined by light (B3) (Figure 9). After moving forward, an approach-avoidance conflict would be evoked as soon as we encounter a narrow corridor. On one hand, the positive valence for the approach is the strong movement factors such as depth and continuity (A4), and on the other hand, a sense of fear from falling down through the narrow space accounts for the negative valence. But when we give courage and step further in the narrow corridor, suddenly this white light turns into a blue color that manifests the sky (B1). From now on, a current of movement would be stimulated ranging from bodily movements, to mental and sensory. First, the explorer aligns their body (A2) with the verticality defined by the concave

Figure 9. A sequence of movement in Copula module in ISS (Source: NASA, 2016).

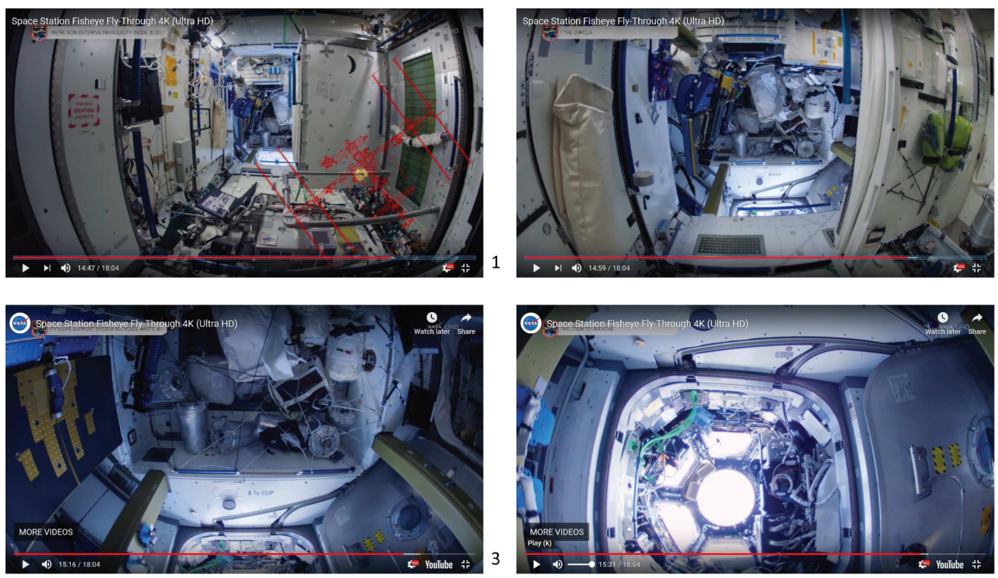
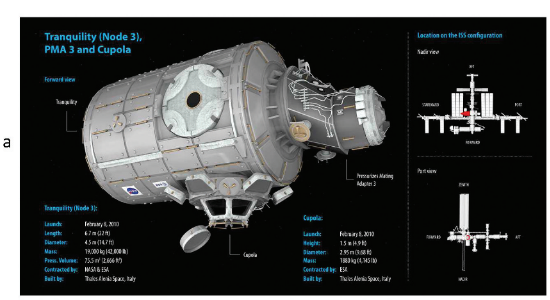


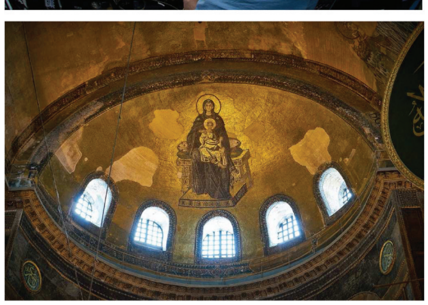
Figure 10. Interior (a) and exterior form (b) of Cupola Module (Credit: NASA). The dome of Hagia Sophia (c) (Credit: The Istanbul Insider).

a



b

Source a: https://www.nasa.gov/content/astronaut-alexander-gerst-checks-out-station-cupola
Source b: https://spacecraftearth.com/wp-content/uploads/2017/06/Tranquility-Node-3-complete.jpg
Source c: https://theistanbulinsider.com/wp-content/uploads/2019/06/hagia-sophia-inside-02.jpg



c

shape of the window (Figure 10(a)) (B2) followed by an evoked reminiscence of medieval domes of sacred places (Figure 10(c)) (B1). Secondly, as is made for observation purposes, Cupola offers a wide dynamic range of view to stimulate a rich movement of the eye in every direction through seven windows (B4). Observing earth with all its magnificence through these windows would rise our awe intrinsically (A5).

On the whole, what is obvious from this narrative is that to get the experience of movement enriched in all three aspects indicated in Table 1, both space and form need to be reconsidered. On one hand, the form should be manifested in the appearance of a living organism to interact more with the perceiver. On the other hand, space, formerly regarded as neutral, now is a liquid in which body floats. Therefore, this space requires special grammar in terms of navigation.

10. Conclusion

This study investigated movement in architecture throughout various documents dealing with how movement in confined habitats might be. It was shown that different stresses are involved in impeding the experience of movement in architecture. Therefore, to get movement in architecture properly experienced and manifested, we need to reduce stressful and unwanted valences induced in space. Besides, diverse types, factors, and architectural elements of movement in orbital space were explained. The main goal of assessing the design of an orbital habitat would be achieved in the form of a taxonomy for the qualitative assessment of "Movement in Orbital Architecture" (Table 1). This table categorizes the interconnections among different types of movement by regarding stressors in the habitats. Through a narrative about how movement occurs in space, there is a possibility to determine how successful space has been built—in terms of generating a balanced experience of movement. At the end, based on the observations carried out on Cupola Module, it is evident that the experience of movement in its space is not enhanced as much as the perceived movement in the form of the dome.

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correction
This article has been republished with minor changes. These changes do not impact the academic content of the article.

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Notes

1. Inversion illusion occurs after a sudden shift in direction. When a shuttle enters the microgravity realm the position of our body becomes the reference for indicating up and down or it remains undetermined (Glasauer & Mittelstaedt, 1998). This poses a major problem for orientation and movement if local vertical is neglected. Despite that, by getting the resort's surfaces defined (e.g., where the ceiling and walls are) this discordance can be alleviated. In the normal condition on earth, our visual and proprioceptive sensation inputs match with vestibular inputs of orientation that leads to a balanced movement (St George & Fitzpatrick, 2011). The vestibular system works relative to gravitational pull (Venkat, 2018). Therefore, this system is not reliable in weightlessness as much as visual and proprioceptive sensation, when one is getting in position to move. Thus, our information about direction remains subjected to the "linear accelerations of the body" (Kanas & Manzey, 2008, p. 50). The lack of proper correspondence among these three systems' inputs produces "space motion sickness" (De la Torre, 2014)—this prodigy can be also generated by the fast movement of head or body.
2. It is not redundant to state that by designing a spinning sphere or a huge cylindrical ring which rotates about its center, an artificial gravity would be created allowing occupants to normally get around in a 1*g* induced gravity. A major advantage of this technology is its engineering which is less complicated than engineering for human propelling in weightlessness (Hall, 2016). Besides, Physical deconditioning stressor would be eliminated once an artificial gravity is applied in the designing. However, the status quo of artificial gravity presents some challenges ranging from health issues, such as problems associated with "vestibular functioning" (Kanas & Manzey, 2008, p. 26), to problems of energy harnessing and "high energy consumption" (Van Alebeek, 2014, p. 35), as well as difficulties of conceiving one-dimensional vanishing line in lieu of the casual zero-dimensional vanishing points (Scharmen, 2018). Furthermore, lesser uniform field of simulated gravity (Hall, 2016) yields a lesser uniform pace of movement, therefore one solution might be through modifications in the geometry of designs to compensate for the variable gravity. For example, in Stanford torus the simulated gravity varies in different point which can be compensated for by altering it to a "Truncated Toroidal Design" (Misra, 2010); this offers a plane flooring. The

amount of g-force would be determined by radius and frequency of rotation that has been proposed to be around 1/60 Hertz in terms of tolerability (Scharmen, 2018). Moreover, "Coriolis direction" would influence any vertical movement. If it is ignored, the likelihood of falling —for instance, in climbing a ladder—would rise (Hall, 2016). Until the scheme of simulated gravity becomes practical, these challenges should be noticed, and the abovementioned designing strategies should be practiced. Additionally, any built space should be designed resiliently to meet both requirements of an environment with and without artificial gravity considering two factors: first the probability of halting the rotation (returning to the weightlessness condition), and secondly, considering the benefit of microgravity for the feasibility of transportation.

3. Other kinds of illusions relative to mind that occur in space are as follows: (1) perceived motion of oneself (when visual perception of movement dominates vestibular inputs) (Kanas & Manzey, 2008, p. 57); (2) inversion illusion or cue-free inversion (when interior does not possess any cue to show verticality) (Dubois, 1994); and (3) illusion of swimming (Ackermann & Liappi, 2016).
4. This illustration is kinetic (for better understanding refer to the source of the figure).

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