ARTIFICIAL GRAVITY AND THE ARCHITECTURE OF ORBITAL HABITATS

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This paper examines the rationale, requirements, limitations and implications of artificial gravity in the design of orbital habitats. Long-term exposure to weightlessness leads to a chain-reaction of undesirable physiological adaptations. There is both theoretical and experimental evidence that artificial gravity can substitute for natural gravity to maintain health in orbit. Aerospace medical scientists have conducted many studies during the past forty years to determine the comfort boundaries for artificial gravity. They express comfort in terms of centripetal acceleration, head-to-foot gravity gradient, angular velocity, tangential velocity, cross-coupled head rotations and the Coriolis effects of relative motion in rotating environments. A review of the literature reveals the uncertainty in these boundaries and suggests that "comfort" in artificial gravity depends as well on other aspects of environmental design, beyond the basic rotational parametres. Artificial gravity is distinct from both Earth-normal gravity and weightlessness. The goal of architectural design for artificial gravity is not to mimic Earth but rather to help the inhabitants adapt to the realities of their rotating environment.

1.   INTRODUCTION

The commercialization of outer space may depend upon an increased human presence in orbit, despite advances in automation and remote control. More people from a broader spectrum of the population will live in orbit for longer periods of time. This is the explicit goal of space tourism. One may suspect that it is the implicit goal of other commercial ventures as well, where space-based research and manufacturing are the means rather than the end.

If the costs of launch and reentry are significant compared to the per-day cost of lodging in space, and if the space habitat is comfortable, then it is reasonable to expect that clients or guests will want to maximize the duration of each visit, to get the most value for their money. Moreover, an experienced and efficient crew may need to serve tours of duty several times as long as the average guest visit.

Unfortunately, long-term exposure to weightlessness leads to a chain-reaction of undesirable physiological adaptations. Countermeasures such as diet and exercise have been only partially effective in preserving health, even for well-trained highly-motivated crews. Use of therapeutic equipment is expensive in time and volume and may be unworkable with a large diverse population.

There is both theoretical and experimental evidence that artificial gravity can substitute for natural gravity to maintain health in orbit. In the early days of space flight, experts assumed that space stations would incorporate artificial gravity. Romantic images of life in orbit have often envisioned space habitats as graceful rotating structures. The novelty of artificial gravity may be one of the features, along with easy access to weightlessness, that attracts people to space tourism.

Artificial gravity is often presented as a panacea for all of the ills associated with prolonged weightlessness. While extensive study has been devoted to the design of the artifact (structure, stability, propulsion and so on), relatively little has been written about the design of the environment, from the point of view of an inhabitant living and moving within it. It has been assumed that artificial gravity should permit the adoption of essentially terrestrial designs. The artificiality of the gravity has been downplayed. Nevertheless, saccharin is not sucrose and centripetal acceleration is not Earth gravity.

2.   ADAPTATIONS TO WEIGHTLESSNESS

It is ironic that, having gone to great expense to escape Earth gravity, it may be necessary to incur the additional expense of simulating gravity in orbit. Before opting for artificial gravity, it is worth reviewing the consequences of long-term exposure to weightlessness.

(1)   **Fluid redistribution**: Bodily fluids shift from the lower extremities toward the head. This precipitates many of the problems described below [1,2].

(2)   **Fluid loss**: The brain interprets the increase of fluid in the cephalic area as an increase in total fluid volume. In response, it activates excretory mechanisms. This compounds calcium loss and bone demineralization. Blood volume may decrease by 10 percent, which contributes to cardiovascular decondistioning. Space crew members must beware of dehydration [1,3].

(3)   **Electrolyte imbalances**: Changes in fluid distribution lead to imbalances in potassium and sodium and disturb the autonomic regulatory system [2,3].

(4)   **Cardiovascular changes**: An increase of fluid in the

thoracic area leads initially to increases in left ventricular volume and cardiac output. As the body seeks a new equilibrium, fluid is excreted, the left ventricle shrinks and cardiac output decreases. Upon return to gravity, fluid is pulled back into the lower extremities and cardiac output falls to subnormal levels. It may take several weeks for fluid volume, peripheral resistance, cardiac size and cardiac output to return to normal [3,4,5].

(5) **Red blood cell loss**: Blood samples taken before and after American and Soviet flights have indicated a loss of as much as 0.5 liters of red blood cells. Scientists are investigating the possibility that weightlessness causes a change in splenic function that results in premature destruction of red blood cells. In animal studies there is some evidence of loss through microhemorrhages in muscle tissue as well [5,6].

(6) **Muscle damage**: Muscles atrophy from lack of use. Contractile proteins are lost and tissue shrinks. Muscle loss may be accompanied by a change in muscle type: rats exposed to weightlessness show an increase in the amount of "fast-twitch" white fibre relative to the bulkier "slow-twitch" red fibre. In 1987, rats exposed to 12.5 days of weightlessness showed a loss of 40 percent of their muscle mass and "serious damage" in 4 to 7 percent of their muscle fibres. The affected fibres were swollen and had been invaded by white blood cells. Blood vessels had broken and red blood cells had entered the muscle. Half the muscles had damaged nerve endings. The damage may have resulted from factors other than simple disuse, in particular: stress, poor nutrition, and reduced circulation – all of which are compounded by weightlessness; and radiation exposure – which is independent of weightlessness. There is concern that damaged blood supply to muscle may adversely affect the blood supply to bone as well [4,5,6,7].

(7) **Bone damage**: Bone tissue is deposited where needed and resorbed where not needed. This process is regulated by the piezoelectric behaviour of bone tissue under stress. Because the mechanical demands on bones are greatly reduced in micro gravity, they essentially dissolve. While cortical bone may regenerate, loss of trabecular bone may be irreversible. Diet and exercise have been only partially effective in reducing the damage. Short periods of high-load strength training may be more effective than long endurance exercise on the treadmills and bicycles commonly used in orbit. Evidence suggests that the loss occurs primarily in the weight-bearing bones of the legs and spine. Non-weight-bearing bones, such as the skull and fingers, do not seem to be affected [1,2,3,4,5,6,8, 9,10,11,12,13,14,15].

(8) **Hypercalcemia**: Fluid loss and bone demineralization conspire to increase the concentration of calcium in the blood, with a consequent increase in the risk of developing urinary stones [1,4].

(9) **Immune system changes**: There is an increase in neutrophil concentration, decreases in eosinophils, monocytes and B-cells, a rise in steroid hormones and damage to T-cells. In 1983 aboard Spacelab I, when human lymphocyte cultures were exposed in vitro to concanavalin A, the T-cells were activated at only 3 percent of the rate of similarly treated cultures on Earth. Loss of T-cell function may hamper the body's resistance to cancer – a danger exacerbated by the high-radiation environment of space [1,3,5,16].

(10) **Interference with medical procedures**: Fluid redistribution affects the way drugs are taken up by the body, with important consequences for space pharmacology. Bacterial cell membranes become thicker and less permeable, reducing the effectiveness of antibiotics. Space surgery will also be greatly affected: organs will drift, blood will not pool, and transfusions will require mechanical assistance [1,3,17].

(11) **Vertigo and spatial disorientation**: Without a stable gravitational reference, crew members experience arbitrary and unexpected changes in their sense of verticality. Rooms that are thoroughly familiar when viewed in one orientation may become unfamiliar when viewed from a different up-down reference. Skylab astronaut Ed Gibson reported a sharp transition in the familiarity of the wardroom when rotated approximately 45 degrees from the "normal" vertical attitude in which he had trained. There is evidence that, in adapting to weightlessness, the brain comes to rely more on visual cues and less on other senses of motion or position. In orbit, Skylab astronauts lost the sense of where objects were located relative to their bodies when they could not actually see the objects. After returning home, one of them fell down in his own house when the lights went out unexpectedly [4,18].

(12) **Space adaptation syndrome**: About half of all astronauts and cosmonauts are afflicted. Symptoms include nausea, vomiting, anorexia, headache, malaise, drowsiness, lethargy, pallor and sweating. Susceptibility to Earth-bound motion sickness does not correlate with susceptibility to space sickness. The sickness usually subsides in 1 to 3 days [4,5].

(13) **Loss of exercise capacity**: This may be due to decreased motivation as well as physiological changes. Cosmonaut Valeriy Ryumin wrote in his memoirs: "On the ground, [exercise] was a pleasure, but [in space] we had to force ourselves to do it. Besides being simple hard work, it was also boring and monotonous." Weightlessness also makes it clumsy: equipment such as treadmills, bicycles and rowing machines must be festooned with restraints. Perspiration does not drip but simply accumulates. Skylab astronauts described disgusting pools of sweat half an inch deep sloshing around on their breastbones. Clothing becomes saturated [1,19].

(14) **Degraded sense of smell and taste**: The increase of fluids in the head causes stuffiness similar to a head cold. Foods take on an aura of sameness and there is a craving for spices and strong flavorings such as horseradish, mustard and taco sauce [1,4].

(15) **Weight loss**: Fluid loss, lack of exercise and

diminished appetite result in weight loss. Space travelers tend not to eat enough. Meals and exercise must be planned to prevent excessive loss [1,19].

(16) **Flatulence**: Digestive gas cannot "rise" toward the mouth and is more likely to pass through the other end of the digestive tract – in the words of Skylab crewman-doctor Joe Kerwin: "very effectively with great volume and frequency" [1].

(17) **Facial distortion**: The face becomes puffy and expressions become difficult to read, especially when viewed sideways or upside down. Voice pitch and tone are affected and speech becomes more nasal [1].

(18) **Changes in posture and stature**: The neutral body posture approaches the faetal position. The spine tends to lengthen. Each of the Skylab astronauts gained an inch or more of height, which adversely affected the fit of their space suits [1, 20].

(19) **Changes in coordination**: Earth-normal coordination unconsciously compensates for self-weight. In weightlessness, the muscular effort required to reach for and grab an object is reduced. Hence, there is a tendency to reach too "high" [21].

Many of these changes do not pose problems as long as the crew remains in a weightless environment. Trouble ensues upon the return to life with gravity. The rapid deceleration during reentry is especially stressful as the apparent gravity grows from zero to more than one "g" in a matter of minutes. In 1984, after a 237-day mission, Soviet cosmonauts felt that if they had stayed in space much longer they might not have survived reentry [3]. In 1987, in the later stages of his 326-day mission, Yuri Romanenko was highly fatigued, both physically and mentally. His work day was reduced to 4.5 hours while his sleep period was extended to 9 hours and daily exercise on a bicycle and treadmill consumed 2.5 hours. At the end of the mission, the Soviets implemented the unusual procedure of sending up a "safety pilot" to escort Romanenko back to Earth [22].

Soviet cosmonauts Vladimir Titov and Moussa Manarov broke the one-year barrier when they completed a 366-day mission on 21 December 1988. Subsequent Russian missions have surpassed that. These long-duration space flights are extraordinary. They are milestones of human endurance. They are not models for space commercialization.

3. COMPONENTS OF ARTIFICIAL GRAVITY

Acceleration by any force other than gravity provides a body with weight. Gravity acting alone leaves a body in weightless free-fall. Earth weight results not from the downward pull of gravity but from the equal and opposite upward push of the ground.

Artificial gravity arises from centripetal acceleration in rotating environments. Experiments have demonstrated its potential for preserving health in orbit. In 1977 aboard the Soviet satellite Cosmos 936, rats exposed to centrifugation were significantly healthier than non-centrifuged control animals. Centrifugation preserved red blood cells, bone minerals, bone structure and mechanical properties [4]. In 1985 aboard Spacelab D-1, centrifugation preserved T-cell function [16].

Assuming that the environment is unpropelled and that its rotation is constant, artificial gravity depends on the following quantities. (Boldface indicates vectors. Italics indicate scalar magnitudes. Dots above indicate derivatives with respect to time.)

$\mathbf{\Omega}$ is the angular velocity of the environment in inertial space, in radians per second.

$\mathbf{r}$ is the radial position of an object in the environment, measured from the centre of rotation, in metres.

$\mathbf{v}$ is the velocity of the object relative to the environment, in metres per second.

$\mathbf{a}$ is the acceleration of the object relative to the environment, in metres per second-squared.

The total apparent artificial gravity derives from the total inertial acceleration. This is the vector sum of three components:

(1) **Global centripetal acceleration**: This is the "design gravity". It is the only component that is independent of the relative motion of objects within the environment. It depends only on the angular velocity of the environment and the radial position of the object. The acceleration is radial, directed inward toward the axis.

$$\mathbf{A}_{cent} = \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}) \tag{1}$$

(2) **Coriolis acceleration**: This is proportional to the vector product of the environment's angular velocity and the object's relative velocity. It is perpendicular to both. When the relative velocity is parallel to the axis of rotation, the Coriolis acceleration is zero.

$$\mathbf{A}_{Cor} = 2\,\mathbf{\Omega} \times \mathbf{v} \tag{2}$$

(3) **Relative acceleration**: This is generally independent of the environment and may assume any value.

$$\mathbf{a} = \dot{\mathbf{v}} = \ddot{\mathbf{r}} \tag{3}$$

The total apparent artificial gravity is the vector sum of these three components. The apparent "up" direction is aligned with the acceleration:

$$\mathbf{A} = \mathbf{A}_{cent} + \mathbf{A}_{Cor} + \mathbf{a} \tag{4}$$

In the special case of relative motion around the circumference of the environment, in the plane of rotation at constant speed and radius, the three components are parallel. Another expression is convenient for the magnitude of the total gravity. Define two additional quantities:

V_t is the magnitude of the environment's tangential velocity (rim speed) in inertial space.

v_t is the magnitude of the object's tangential velocity relative to the environment.

In this case, the magnitude of the total apparent artificial gravity derives from the following:

$$V_t = \Omega r \tag{5}$$

$$v_t = v \tag{6}$$

$$\Omega = V_t / r \tag{7}$$

$$A_{cent} = V_t^2 / r \tag{8}$$

$$A_{Cor} = \pm 2 V_t v_t / r \tag{9}$$

$$a = v_t^2 / r \tag{10}$$

$$A = A_{cent} + A_{Cor} + a \tag{11}$$

$$= (V_t \pm v_t)^2 / r \tag{12}$$

choosing "+" for prograde and "−" for retrograde motion. The acceleration is radial, directed toward the centre of rotation.

Only the global centripetal acceleration represents "design gravity". The other components are gravitational distortions that arise from motion within the environment. They affect the magnitude and direction of the total acceleration, causing changes in the apparent weight of objects and the apparent slope of surfaces. Taking Earth as the norm, one's experience of gravity should be independent of one's motion. Hence, the goal is to design the environment such that the global centripetal acceleration yields some preferred level of artificial gravity while simultaneously minimizing the other components. The equations suggest that the angular velocity should be kept low and that the radius should be large.

In a rotating system, one must also consider the non-intuitive effects of angular momentum. To turn an object about some local axis, in an environment that is rotating about some other global axis, requires a moment about a third axis perpendicular to the other two. The moment is proportional to the vector product of the environment's angular velocity and the object's angular momentum. The non-aligned rotations about the global and local axes are said to be "cross-coupled".

For example, consider a person standing in a rotating orbital habitat, facing prograde. The habitat may resemble a giant bicycle wheel. Artificial gravity aligns his apparent vertical axis along a radius or "spoke" that rotates with the habitat. The habitat's rotation axis is over head, horizontal in his frame of reference, directed left-to-right. As long as he remains motionless relative to the habitat, he rotates with it effortlessly. When he turns to his left, he adds vertical components to his angular velocity and momentum. His angular momentum is no longer aligned with the habitat's angular velocity. To sustain this leftward turn about his vertical axis (while that axis rotates with the habitat) requires a left-leaning moment about his front-to-back axis. Moreover, this leftward turn about his vertical axis induces effects on his vestibular organs *as if* he was rotating about his front-to-back axis.

Experiments with human subjects in centrifuges and rotating rooms have confirmed this. When subjects turn their heads about any axis that is not aligned with the rotation of the environment, they experience vestibular illusions of rotation about a perpendicular axis. The illusions are approximately proportional in magnitude and direction to the vector product of the angular velocities of the environment and the head [23,24]. The resulting mismatch between the vestibular and visual senses of motion are believed to be a major cause of motion sickness [4,5]. To minimize these illusions while permitting the normal range of human motion, the angular velocity of the environment should be kept low.

Unfortunately, when the radius is limited, reducing the angular velocity may increase other aspects of gravitational distortion. One measure of this distortion is the ratio of the magnitudes of the Coriolis and global centripetal accelerations. To emulate a natural gravitational environment, this ratio should be minimized without constraining the relative motion of people or objects within the environment. Define the following symbols:

v_p is the magnitude of an object's relative velocity in the plane of rotation (including radial and tangential velocity but not axial velocity).

V_t is the magnitude of the environment's tangential velocity (rim speed) in inertial space.

A_{Cor} is the magnitude of the Coriolis acceleration:

$$A_{Cor} = | 2\, \boldsymbol{\Omega} \times \mathbf{v} | = 2\Omega v_p \tag{13}$$

A_{cent} is the magnitude of the global centripetal acceleration:

$$A_{cent} = | \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r}) | = \Omega^2 r \tag{14}$$

If decreasing angular velocity is compensated by increasing radius, so that centripetal acceleration remains constant, then decreasing angular velocity Ω decreases this ratio:

$$A_{Cor} / A_{cent} = 2\Omega v_p / A_{cent} \tag{15}$$

However, once the maximum feasible radius is reached, further reduction of angular velocity Ω decreases both the Coriolis *and* centripetal accelerations and *increases* the *ratio* of Coriolis to centripetal:

$$A_{Cor} / A_{cent} = 2\Omega v_p / \Omega^2 r$$
$$= 2v_p / \Omega r$$
$$= 2v_p / V_t \tag{16}$$

Thus for any given radius, while reducing Ω ameliorates problems associated with rotational cross-coupling (such as dizziness, ataxia, and nausea), it exacerbates gravitational distortion.

4.   COMFORT CRITERIA IN ARTIFICIAL GRAVITY

It was long assumed that manned space stations would rotate to provide artificial gravity. Tsiolkovsky, Oberth, Noordung, von Braun and other visionaries performed detailed calcu-

lations and published various concepts for rotating space stations several decades before the first Sputnik entered Earth orbit.

The physical theory behind artificial gravity is as old as Isaac Newton's *Principles*. Nevertheless, there was no significant research into the human factors of artificial gravity until Sputnik inaugurated the "space race". With the beginning of manned space flight in the 1960s, there was concerted effort to determine the comfort criteria for rotating habitats. In the USA, much of this research took place in centrifuges, rotating rooms and rotating space station simulators at the Naval Aviation Medical Acceleration Laboratory (Johnsville, Pennsylvania), the Naval Aerospace Medical Research Laboratory (Pensacola, Florida) and the NASA Langley Research Centre (Hampton, Virginia).

As experience with weightless space flight accumulated, artificial gravity assumed a lower priority. The NASA Langley simulator was dismantled in the early 1970s. Since the beginning of the Salyut and Skylab missions, access to a micro-gravity environment has been one of the main motivations for space flight. Ironically, while extended stays in weightlessness have revealed its dangers, they have also shown that it is survivable. Artificial gravity is now discussed primarily in the context of interplanetary missions, in which long periods of weightless coasting through empty space are an annoyance, not an objective.

Hence, much of the research into the human factors of rotating habitats is twenty or thirty years old. Over the past four decades, several authors have published guidelines for comfort in artificial gravity, including graphs of the hypothetical "comfort zone" bounded by values of acceleration, head-to-foot acceleration gradient, rotation rate and tangential velocity. Individually, these graphs depict the comfort boundaries as precise mathematical functions. Only when studied collectively do they reveal the uncertainties [23,25,26,27,28,29].

In 1960, Clark and Hardy noted that "normal" head rotations may occur at up to 5 sec^{-1} (that is, 5 radians per second). They performed centrifuge studies and observed that the rotational cross-coupling thresholds were 0.06 sec^{-2} for vestibular illusions and 0.6 sec^{-2} for nausea. They proposed to stay completely below the threshold of illusions and concluded that the station rotation should not exceed about 0.01 sec^{-1} (that is, the 0.06 sec^{-2} threshold for illusions divided by the 5 sec^{-1} head rotation). At 0.01 radians per second, a 1-g station would need a radius of 98,000 metres [23].

In 1973, Stone assumed "normal" head rotations of only 3 sec^{-1} (rather than 5) and acceptable cross-coupling up to 2 sec^{-2} (more than three times the nausea threshold predicted by Clark and Hardy), giving a maximum station rotation of 0.67 sec^{-1}. This is 67 times the maximum rate proposed by Clark and Hardy and brings the radius of a 1-g station down to only 22 metres [28].

Perhaps the most enlightening commentary on human adaptation to a rotating environment was published by Graybiel in 1977 [30]:

"In brief, at 1.0 RPM even highly susceptible subjects were symptom-free, or nearly so. At 3.0 RPM subjects experienced symptoms but were not significantly handicapped. At 5.4 RPM, only subjects with low susceptibility performed well and by the second day were almost free from symptoms. At 10 RPM, however, adaptation presented a challenging but interesting problem. Even pilots without a history of air sickness did not fully adapt in a period of twelve days."

Table 1 summarizes several estimates of the comfort boundaries for artificial gravity. Since various authors define the parametres slightly differently, a side-by-side comparison requires some interpretation.

(1) **Year of publication**: In some cases, the publication of conference proceedings lagged the conferences by two or three years. This does not affect the chronological order of the estimates in Table 1. The chronology shows the trends, or lack thereof, in the estimates of the various boundaries.

TABLE 1: *Comfort Boundaries in Artificial Gravity.*

Author	Year of Publication	Min. Apparent Gravity	Max. Apparent Gravity	Max. Apparent Gravity Gradient per Meter	Max. Angular Velocity of Habitat	Min. Tangential Velocity of Habitat
		$A / 9.81$	$A / 9.81$	$\Delta A / A_{ref}$	$30\,\Omega / \pi$	$V_t = \Omega\, r$
Clark & Hardy [23]	1960	—	—	—	0.1 rpm	—
Hill & Schnitzer [25]	1962	0.035 g	1 g	—	4 rpm	6 m/s
Gilruth [26] "optimum"	1969	0.3 g	0.9 g	8 %	6 rpm 2 rpm	—
Gordon & Gervais [27]	1969	0.2 g	1 g	8 %	6 rpm	7 m/s
Stone [28]	1973	0.1 g	1 g	25 %	6 rpm	10 m/s
Cramer [29]	1985	0.1 g	1 g	0.03 g	3 rpm	7 m/s

(2)   **Apparent gravity**:   This is stated in multiples of Earth gravity:

$$1\ g\ =\ 9.81\ m/s^2$$

Most authors apply these limits solely to the global centripetal acceleration (the nominal "design gravity"):

$$\begin{aligned} A\ &=\ \Omega^2\, r \\ &=\ V_t^2\, /\, r \end{aligned}$$

Stone applies them to the total acceleration, including the Coriolis and relative components, when walking prograde or retrograde at 1 metre per second:

$$\begin{aligned} A\ &=\ \Omega^2\, r \pm 2\Omega + 1\,/\,r \\ &=\ (V_t \pm 1)^2\,/\,r \end{aligned}$$

(a)   *Minimum apparent gravity*:   This parametre usually aims to provide adequate floor traction for mobility.   In the case of Hill and Schnitzer, it appears to be an arbitrary lower bound on a logarithmic scale.   The minimum required to preserve health remains unknown.

(b)   *Maximum apparent gravity*:   For reasons of both comfort and cost, this generally should not exceed 1 g.   Gilruth gives no explanation for his specification of 0.9 g.   Similar to Stone, he may be allowing for some inevitable increase from the extra accelerations while walking prograde.

(3)   **Maximum apparent gravity gradient per metre**: This is a decrease in apparent gravity over a radial distance of 1 metre, divided by some reference value.

(a)   *Relative gradient*:   When the gradient is given as a percentage, the reference value is the apparent gravity at the floor:

$$\Delta A\,/\,A_{ref}\ =\ (A_{floor} - A_{floor-1})\,/\,A_{floor}$$

When this is applied only to centripetal acceleration, it directly determines the floor radius.   For example, a 25% gradient per metre in centripetal acceleration implies a floor radius of 4 metres.

(b)   *Absolute gradient*:   When the gradient is given as a definite "g" value, the reference is Earth gravity:

$$\Delta A\,/\,A_{ref}\ =\ (A_{floor} - A_{floor-1})\,/\,9.81$$

Most authors specify a percentage gradient over a "head-to-foot" distance of 2 metres or 6 feet.   Cramer specifies an absolute gradient, so the percentage depends on the selected value for the apparent gravity at the floor.

(4)   **Maximum angular velocity of habitat**:   This is stated in rotations per minute:

$$\begin{aligned} 1\ rpm\ &=\ (2\pi\,/\,60)\ radians\ per\ second \\ &=\ (\pi\,/\,30)\ s^{-1} \end{aligned}$$

The limit aims to avoid motion sickness caused by the cross-coupling of normal head rotations with the habitat rotation.   The value depends largely on the susceptibility of the inhabitants and the time permitted for their adaptation.   Lower values accommodate a broader sample of the general population.   Gilruth specifies 6 rotations per minute for "comfort" but only 2 for "optimum comfort".   In this context, "comfort" does not imply luxury but merely mitigation of symptoms.

(5)   **Minimum tangential velocity of habitat**:   This should be large compared to the relative velocity of objects within the habitat.   The goal is to keep the Coriolis acceleration small in proportion to the global centripetal acceleration.   (For relative motion in the plane of rotation, the ratio of Coriolis to global centripetal acceleration is twice the ratio of relative velocity to habitat tangential velocity.   (See Eq. 16 above.)   Hill and Schnitzer specify a tangential velocity of at least 6 metres per second (20 feet per second) so that walking prograde or retrograde will not change one's apparent weight by more than 15%. Even so, a person would have to walk very slowly – less than 0.5 metres per second – to stay within the 15% limit.   Stone proposes that an object's apparent weight should not change by more than 25% when carried at 1.2 metres per second.   This implies a minimum habitat tangential velocity of about 10 metres per second.

One would hope that later publications would be more reliable or up-to-date than earlier ones.   Nevertheless, the comfort chart published by Hill and Schnitzer in 1962 seems to be the most persistent.   Perhaps this is because they published in a monthly journal with a wide circulation, whereas subsequent authors published in conference pro-ceedings with much smaller audiences.   Twenty-five years later, artificial-gravity engineering studies were still citing Hill and Schnitzer [31,32].

5.   ENVISIONING ARTIFICIAL GRAVITY

The comfort criteria described above are succinct summa-ries of abstract mathematical relationships, but they do nothing to convey the look and feel of artificial gravity. Consequently, there has been a tendency in many design concepts to treat any point within the hypothetical comfort zone as "essentially terrestrial", although that has not been
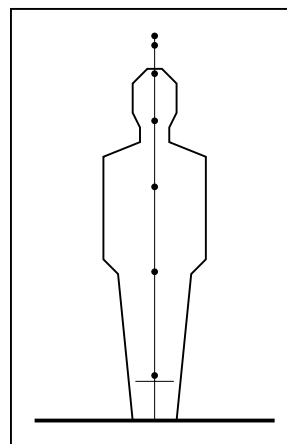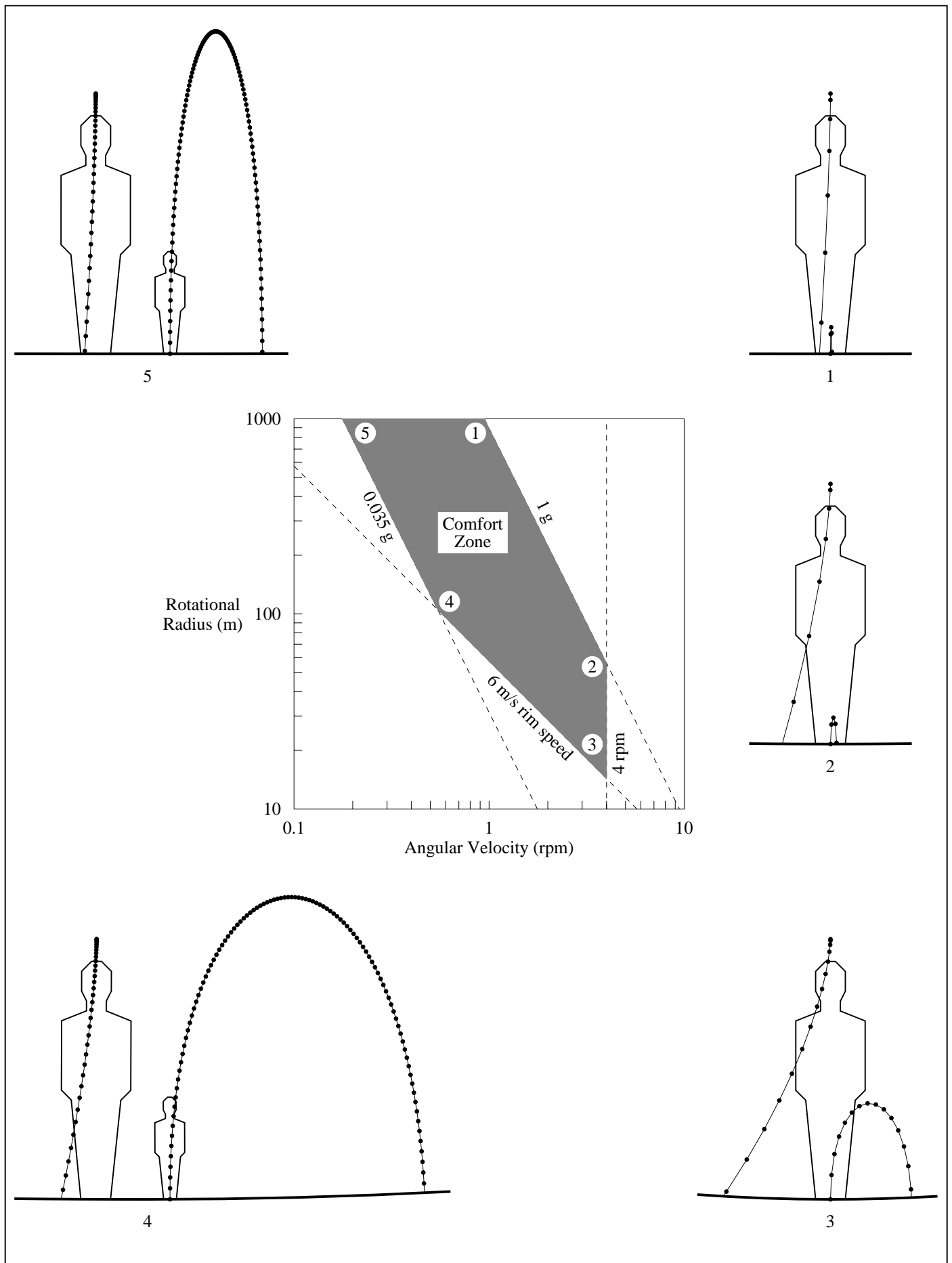

Fig. 1 Earth-Normal Gravity.

Fig. 2 Artificial Gravity and the Comfort Zone.

the criterion for defining the zone. The defining criterion has been "mitigation of symptoms" and authors differ as to the boundary values that satisfy it. This suggests that the comfort boundaries are fuzzier than the individual studies imply. Comfort may be influenced by task requirements and environmental design considerations beyond the basic rotational parametres.

Perhaps a more intuitive way to compare artificial-gravity environments with each other as well as with Earth is to observe the behaviour of a free-falling object when dropped from a certain height or launched from the floor with a certain velocity. Figure 1 shows, for Earth-normal gravity, the effects of launching a ball vertically from the floor with an initial velocity of 2 metres per second, and of dropping a ball from an initial height of 2 metres. The "hop" and the "drop" each trace vertical trajectories. The "hop" reaches a maximum height of 0.204 metres, indicated by a short horizontal line. The "drop" is marked by dots at 0.1-second intervals. Figure 2 shows a typical comfort chart for artificial gravity, after that of Hill and Schnitzer, surrounded by five similar "hop and drop" diagrams – one for each boundary point of the comfort zone. When compared with the Earth-normal standard of fig. 1, these diagrams reveal certain features of the comfort boundaries:

(1) **Large radius** (points 5 and 1): Artificial gravity becomes increasingly "normal" as the radius of rotation approaches infinity. The trajectory of a dropped object depends only on the radius of rotation and the initial height of the object. Thus, the drops at points 5 and 1 follow congruent paths, although the drop at 5 is much slower due to the low gravity. (The dots are spaced at 0.1-second intervals.) The trajectory of a thrown object is influenced by the ratio of its initial relative velocity to the habitat's tangential velocity. Thus the hop at point 5, besides being much higher (due to the low gravity), is also more distorted than at point 1 due to the lower tangential velocity. Point 1 is the most "Earth-normal" point on the chart. Point 5 approaches "normal" for a planetesimal or asteroid.

(2) **Earth gravity** (points 1 and 2): Earth-magnitude does not imply Earth-normal. Although both points represent 1-g environments, both the hop and the drop are more distorted at point 2, due to the smaller radius and lower tangential velocity.

(3) **High angular velocity** (points 2 and 3): The upper limit of angular velocity is determined by the onset of motion sickness due to cross-coupled rotations. At this boundary, reducing the radius reduces the centripetal acceleration and tangential velocity as well. As judged by the "twisting" of the apparent gravity, point 3 is the least normal point in the comfort zone.

(4) **Low tangential velocity** (points 3 and 4): For a given relative motion, the ratio of Coriolis to centripetal acceleration increases as tangential velocity decreases. Between points 3 and 4 it is constant. Hence, the hops at these points have similar shapes, though the hop at point 4 is larger due to the lower acceleration. The drop at point 4 is

straighter due to the larger radius.

(5) **Low gravity** (points 4 and 5): Although the centripetal acceleration at these points is equal, the gravity is less distorted at point 5 due to the larger radius and higher tangential velocity.

Evidently, the comfort zone encompasses a wide range of environments, many of them substantially non-terrestrial. Conformance to the comfort zone does not guarantee an Earth-normal gravity environment, nor does it sanction "essentially terrestrial" design.

6. ARCHITECTURE FOR ARTIFICIAL GRAVITY

In the twenty-five years since the Skylab workshop, micro-gravitational habitat design has progressed from an almost anti-terrestrial disregard for Earth-normalcy to a realization that some Earth norms can serve a useful coordinating function. One now sees designs for orbital habitats that provide distinct "Earthy" floor, wall, and ceiling references and consistent cues for vertical orientation, without denying either the possibility of ceiling-mounted utilities or the necessity of foot restraints.

Exactly the opposite sort of progression is needed in artificial-gravity design. Most concepts published to date have implied complete Earth-normalcy with regard to perceived gravity, stability, and orientation. A more appropriate approach calls for preserving those Earthly elements that serve a positive function while incorporating modifications that accommodate the peculiarities of rotating environments.

An important organizing theme in architectural design theory is the notion of principal directions, which imbue space with an inherent structure. The identification of these directions is powerfully influenced by gravity.

In terrestrial architecture, six directions on three axes are innately perceptible: up-down (height), left-right (breadth), and front-back (depth). The up-down axis is normally tied to the force of gravity. The other axes are free to rotate around it. The up-down axis is called "vertical", while all possible left-right and front-back axes are called "horizontal". The anisotropic character of this space is judged by the effort required to move in any given direction: up and down are distinct irreversible poles. Left, right, front and back are inter-changeable simply by turning around. Thus, gravitationally, there are three principal directions – up, down, and horizontal – and three basic architectural elements – ceiling (or roof), floor, and wall. The walls, which bound the horizontal dimensions, are not inherently distinct.

These common-sense ideas, rooted in the experience of terrestrial gravity, permeate architectural theory. Thiis-Evensen builds his entire grammar around the three elements of floor, wall, and roof [33]. Architectural design for a gravitational environment distinctly different from Earth's requires a fundamental reexamination of design principles which until now have been taken for granted. According to Norberg-Schulz [34]:

"To be meaningful … the inventions of man must have formal properties which are structurally similar to

other aspects of reality, and ultimately to natural structures … Natural and man-made space are structurally similar as regards directions and boundaries. In both, the distinction between up and down is valid, as well as the concepts of extension and closure. The boundaries of both kinds of space are moreover to be defined in terms of 'floor', 'wall', and 'ceiling'."

On the one hand, he testifies to the importance of reality and nature (whatever they may mean) in architectural expression. On the other hand, his characterization of the directions and boundaries of natural and man-made space must be reevaluated – if not refuted – in extraterrestrial environments.

With regard to free-fall and relative motion, artificial gravity can be made Earth-normal within any finite tolerance, provided that the radius of rotation is sufficiently large. However, to make the abnormalities imperceptible, "sufficiently large" may be prohibitively expensive. The alternative is to adapt the architecture to the gravitational abnormalities associated with rotation at smaller radii.

In such an environment, falling objects follow involute trajectories and dropped objects deflect noticeably to the "west" (retrograde), as if blown by a sort of "gravitational
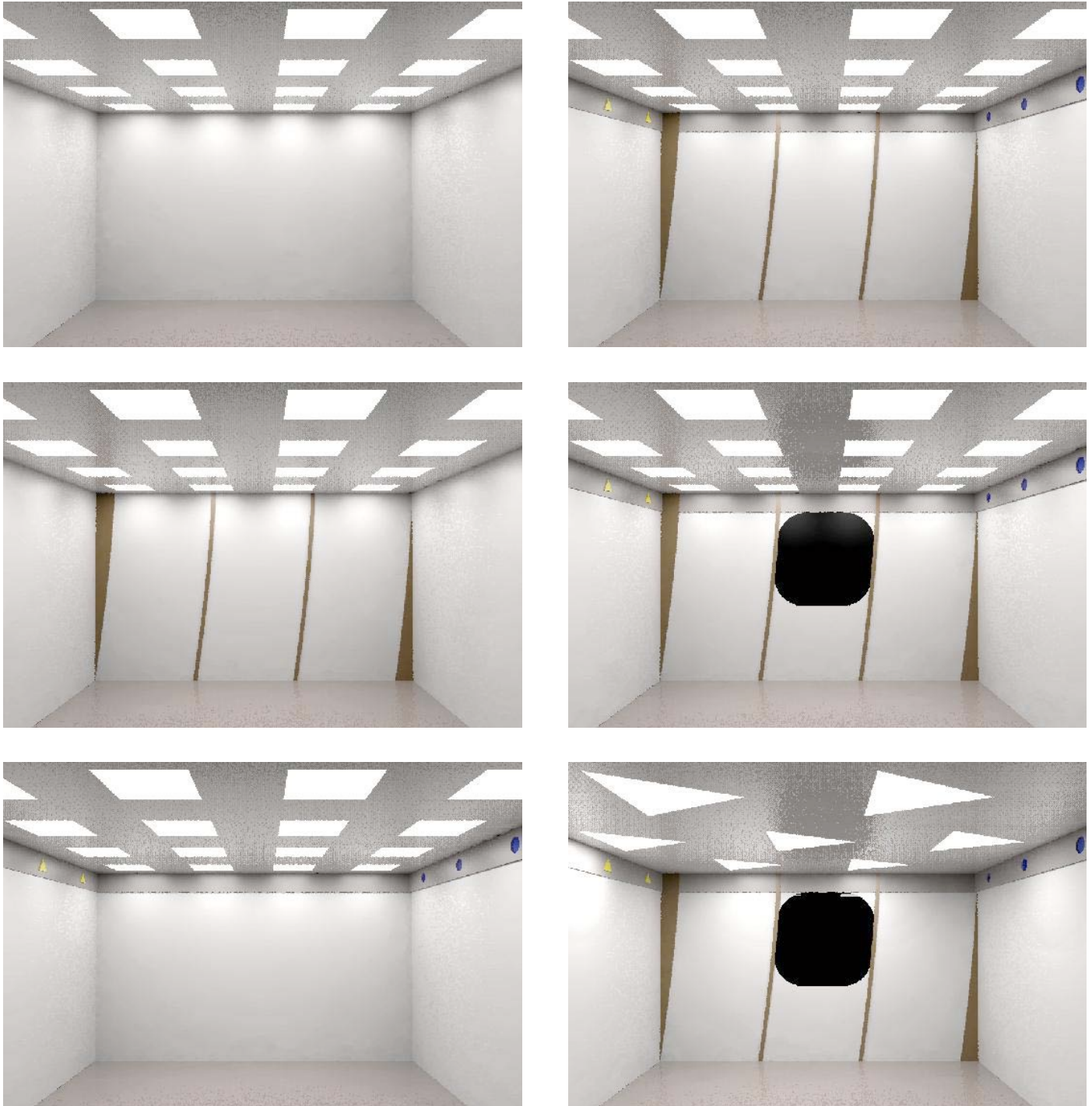

Fig. 3 Experiments in the formal expression of rotation in an artificial-gravity environment.

wind". East (prograde) and west (retrograde) are gravitationally distinct in a manner akin to up and down. Therefore, there are not only three, but at least five principle directions: up, down, east, west and axial. The smaller the radius, the stronger the distinction between east and west. It is an inescapable aspect of artificial gravity that cannot be masked by architecture. Perhaps it follows that "eastwall" and "westwall" must be introduced as new elements in the grammar of architecture.

As a secondary effect, axial is decomposable into "north" and "south" through cross-coupled rotations. If a torque is applied to an object about the up-down axis while the environment spins about the north-south axis, there is a cross-coupling effect about the east-west axis. Turning to the left or right will cause a tendency to tip toward the north or south (about the east-west axis). This effect depends on the object's particular inertia components, so it is a less consistent reference than the free-fall involute curve. Nevertheless, it should be consistent for rotations of the head – the most important object for gravitational orientation.

Unlike up and down, which are continuously distinct, east, west, north and south are intermittently distinct. The distinctions emerge only during relative motion within the rotating environment, in proportion to the relative velocity. While one is stationary, one may forget that there is such a distinction, only to be rudely reminded of it when rising out of a chair or turning to the side. Anything that keeps inhabitants "passively" oriented to the rotation of their habitat would allow them to prepare themselves for the consequences of their actions, thereby aiding their coordination and adaptation.

Hesselgren constructs his architectural theory on the foundations of perception psychology [35,36]. He describes "transformation tendencies" between various senses, whereby a perception in one modality may produce a mental image of a perception in another. For example, visual texture gives rise to a mental image or expectation of tactile grain. One modality that he never discusses, which is taken for granted on Earth but cannot be in space, is vestibular perception. It might be possible, through experience in a properly designed environment, to acquire a transformation tendency to vestibular perception from visual, acoustic, haptic, or other perceptions. The goal is not to induce motion sickness by the mere sight of some visual cue. Rather, it is to provide visual or other reminders that motion relative to these cues will result in certain inescapable side effects, inherent in the artificial gravity. These perceptual cues would act as signals, triggering adaptive coordination in the inhabitants. From the designer's point of view, a consistent "vocabulary" of such signals would have to arise from convention. From the inhabitants' point of view, these conventions might to some extent be taught, but the unconscious transformation to a vestibular image would rely on association based on direct experience.

In designing signals, it is usually best to incorporate multiple perceptions. For example: stop signs are both red and octagonal; no other traffic sign possesses either attribute. One may speculate on the use of colour and form in artificial gravity to distinguish eastwall from westwall. Just as ceilings are usually lighter than floors in colour, one may propose that eastwalls could be tinted with receding colours and westwalls with advancing colours. Thiis-Evensen and Hesselgren both note the receding character of cool colours tending toward blue and the advancing character of warm colours tending toward yellow [33,35,36]. The forms of the eastwall and westwall may incorporate literal casts of the involute curve, or other symbolic shapes such as triangles for advancing (westwall) and circles for receding (eastwall). These forms may be merely chromatic or they may be cast in bas-relief – convex for advancing and concave for receding.

Classical architecture is the premier example of a system of design rules for the proportion and placement of forms [37]. The mathematical precision of the classical orders is a reflection of the order in the Renaissance conception of the universe. One can imagine the invention and evolution of a new set of design rules for artificial gravity, involving, for example, pilasters with involute profile and friezes composed from advancing and receding colours and bas-relief shapes.

I offer this Classical analogy merely as an example, certainly not as a specific recommendation or conclusion. Prak is careful to distinguish between formal and symbolic aesthetics: the former deals with general rules of rhythm, proportion, balance and consistency; the latter with heuristic aspects of style [38]. What is important is that general rules of composition can be developed and applied to the architecture of artificial gravity – to impart, as Norberg-Schulz suggests, formal properties which are structurally similar to other aspects of the environment. The specific style in which this is done will evolve as a function of mission, population and time.

Figure 3 is a sequence of computer images that represent simple experiments with architectural forms in artificial gravity. Starting with an unadorned room and the elements of floor, wall, and ceiling, forms are added or modified to express the rotation of the room in space and the consequent distinction between east and west. The involute curves on the back wall trace the path of a ball dropped from ceiling height, assuming a floor radius of 250 metres – the approximate proposed radius of the "Bernal Sphere" space colony [39]. The frieze (just below the ceiling) is punctuated with recessed blue circles on the eastwall and raised yellow triangles on the westwall. The scene through the window would appear to rotate clockwise at about 1.9 rpm.

The formal approach suggested here is relevant only to the extent that it is adaptive to function in a rotating environment. Forms of one sort or another are unavoidable, whether they result from apathetic adherence to Earth norms or proactive design for a new environment. Good design will require knowledge, empathy and deliberate exploration of alternatives.

7. CONCLUSION

The design of an orbital habitat for artificial gravity depends on much more than physics. A few simple formulae relate the habitat's size and rotation to the apparent gravity. Unfortunately, the formulae are powerless to predict the satisfaction of the inhabitants. Many empirical studies have attempted to identify the comfort boundaries for artificial gravity, to constrain the values of the variables. Nevertheless, they have arrived at substantially different conclusions. The disagreement may be due in part to different

assumptions regarding the mission, selection, motivation and adaptability of the target population. To support a large clientele, it may be safe to stay within the common ground of all of the empirical studies, choosing the most restrictive bounding value for each variable.

Ultimately, an inhabitant's ability to adapt to artificial gravity will depend on how well the habitat itself is adapted. As a matter of principle, it is probably not possible to design for artificial gravity without having lived in it. Nevertheless, in designing the first such habitats, one must make the effort.

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