# Space Settlement Population Rotation Tolerance

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## Abstract

To avoid a number of very negative health effects due to micro-g, free-space settlements may be rotated to provide 1g of artificial gravity. Since the NASA/Stanford space settlement studies of the 1970s the settlement design community has assumed that rotation rates must be no more than 1-2 rpm to avoid motion sickness. To achieve 1g, this rotation rate implies a settlement radius of approximately 225-895 m, which is much larger than any existing satellite. In this paper we examine the literature and find good reason to believe that much higher rotation rates may be acceptable to residents and visitors alike, significantly reducing the minimum size of settlements and thus the difficulty of building them. We find that rotation rates of up to 4 rpm, corresponding to a 56 m radius, should be acceptable, although visitors may require some training and perhaps a day or so of adaptation for those particularly susceptible to motion sickness. A rotation rate of up to 6 rpm (25 m radius) should be acceptable for residents but visitors will almost certainly need training and/or a few days to adapt. While higher rotation rates (up to 10 rpm) may be acceptable with training, such small structures are not suitable for permanent residence (9 m radius at 10 rpm). With some caveats due to the quality of the available data, it appears that the lower limit of space settlement size is not determined by human response to rotation rate but rather by other factors. This means that the effort necessary to build the first space settlements may be significantly less than previously believed, simply because they can be much smaller than heretofore expected.

## Introduction

When designing space settlements, size is a key parameter. The smaller the size, all else being equal, the easier a settlement will be to build. How small can a free-space settlement be? Examining the human tolerance of rotation literature we find that the minimum size is not determined by the rotation rate necessary to achieve a 1g artificial gravity environment for the residents, but rather by other concerns which may include psychological, social factors and environmental stability. We do not examine these other factors.

A space settlement is a permanent community living in space. Unlike a space mission, a settlement is intended to be permanent. Unlike a space station or base, which is more like a work camp, a settlement is a place where children are raised. The requirement to raise children puts severe constraints on the living environment of a space settlement, at least for the first few generations. Specifically, children raised in anything significantly less than Earth-normal gravity, or something similar, can be expected to have weak bones and muscles as these develop in response to stress. There may be other problems as well.

From hundreds of space flights we know that adults suffer many adverse effects from temporary micro-g[1] living, some of which are quite serious. There is also a little data on 0.17 g adult exposure from the twelve astronauts who walked on the Moon, but not enough to draw any conclusions.

There is no data on the effects of altered gravity levels on children. As one must be conservative where children's health and well being are concerned, the authors believe that at least the first few generations to live in space should provide something similar to Earth-normal gravity to their children.

If a space settlement is in orbit (a free-space settlement), as opposed to the surface of a body such as the Moon or Mars, it can be rotated to provide artificial gravity at Earth-normal levels (1g). Such space settlements were proposed by Princeton professor Gerard O'Neill. A series of NASA/Stanford studies in the 1970s suggested that with sufficient effort such settlements could be built and operated [Johnson 1975, O'Neill 1977]. However, living in a rotating environment is known to cause various problems, most of which are associated with vestibular function [Hall 1994].

The 1970s space settlement studies assumed that a rotation rate of no more than 1-2 rpm[2] was acceptable. Since the centripetal force[3] to mimic gravity generated by rotation is a function of rotation rate and distance from the axis of rotation, this implies a radius of at least 225 m (corresponding to 2 rpm). Such large structures are difficult to build and require a great deal of materials, which are essentially non-existent in orbit and thus must be imported from the Earth, Moon, or asteroids. If the rotation rate could be increased, the first free-space settlements could be significantly smaller and, thus, easier to build.

[1] g - the acceleration due to gravity at the surface of the Earth.
[2] rpm - rotations per minute
[3] centripetal force - the force necessary to keep a body rotating around a given axis. This force is always in a direction towards the axis of rotation and prevents objects from flying off into space. In a free-space settlement, the centripetal force is generated by the hull of the spacecraft as it rotates.

To achieve 1 g artificial gravity at a given rotation rate, the following radius is necessary:

| rotation rate (rpm) | radius (m) |
|---|---|
| 1 | 895.47 |
| 2 | 223.87 |
| 3 | 99.50 |
| 4 | 55.97 |
| 5 | 35.82 |
| 6 | 24.87 |
| 7 | 18.27 |
| 8 | 13.99 |
| 9 | 11.06 |
| 10 | 8.95 |

Note that increasing the rotation rate yields relatively small decreases in system size after about six rpm (only a six meter reduction in radius from six to seven rpm). Thus, rotation rates greater than about six rpm provide little benefit in terms of ease of settlement construction.

## Space Settlement Rotation

This paper reviews the existing literature on human rotation tolerance with an eye on issues relevant for space settlement. The references supporting the assertions in this section can be found below where the discussion is more extensive. Also, there are some important caveats as to the authority of the existing data. The studies

- have very few subjects, usually 10 or less.
- show great variability in rotation tolerance from person to person.
- sometimes chose subjects for higher than normal rotation tolerance.
- have only adult subjects.
- are only a few weeks or less in duration.
- often rotate subjects around a different body axis than would a free-space settlement (e.g. upright on a turntable, spine perpendicular to the centripetal acceleration, versus spine parallel to the centripetal acceleration).
- do not consider how environmental design might help or hinder adaptation.
- use rotational experiment environments with very short radii of rotation, typically under 4 m (there is one exception). This means the effects observed in these experiments are likely much more severe than in a settlement as most effects attenuate with larger radii.
- are almost all on the surface of the Earth and there is evidence that the negative effects of rotation are much less in an otherwise weightless environment.

It's also important to note that there will be two classes of people subject to the rotation of a space settlement: residents and visitors. While accommodating visitors is definitely desirable, it's worth noting that even on Earth there are many settlements that are not immediately comfortable to all visitors.

Residents will be exposed to rotation almost their entire lives. While the rotation rate will be constant, the distance to the axis of rotation will not and some effects are a function of the radius of rotation. This means residents must adapt to many different rotational environments. There is some evidence this can be done.

Visitors may be presumed to start their trip in a non-rotating space vehicle. To dock, this vehicle or some interface mechanism must rotate up to the rate of the settlement, and this will involve a short radius of rotation as the transport vehicle can be expected to be small compared to a settlement. However, visitors will not spend a great deal of time in this environment as they can quickly move into the settlement and transit to the outer rim where the radius of rotation is much larger. This whole process must be reversed when the visitor leaves, which can also cause problems. Fortunately, much of the literature is relevant to visitors spinning up and down with a short radius of rotation.

Based on our examination of the literature (see below), our recommendations for settlement rotation rate is as follows:

- Up to 2 rpm should be no problem for residents and require little adaptation by visitors.
- Up to 4 rpm should be no problem for residents but will require some training and/or a few hours to perhaps a day of adaptation by visitors.
- Up to 6 rpm is unlikely to be a problem for residents but may require extensive visitor training and/or adaptation (multiple days). Some particularly susceptible individuals may have a great deal of difficulty.
- Up to 10 rpm adaptation has been achieved with specific training. However, the radius of a settlement at these rotation rates is so small (under ~20 m for seven rpm) it's hard to imagine anyone wanting to live there permanently much less raise children.

The literature suggests that training consisting of a series of specific repeated head movements while in a rotating environment can be helpful. The repeated head movements generate repeated, consistent stimulus to the otolith organs[4] that sense gravity and acceleration and send signals to the brain. Repeating the stimulus allows the brain to adapt to the coriolis[5] forces generated by motion in a rotating environment. Some, or perhaps even all, of this training could be done on the ground before flight.

[4] The otolith organs are structures in the inner ear that are sensitive to gravity and acceleration.
[5] The Coriolis effect involves deflection of an object caused by moving in a rotating environment.

The data these recommendations are based on involves short radii of rotation, usually only a few meters. Since space settlements will have much larger radii of rotation (e.g., 25 m at 6 rpm) and negative effects decline with increasing radii, these recommendations are quite conservative. In other words, high rotation rates may work much better than these recommendations suggest.

Almost, but not quite, all of the studies regarding the negative effects of rotation took place on the surface of the Earth. That means that the otolith organs were exposed to a complex mix of Earth gravitational and rotational effects. On a space settlement, the Earth's gravitational effects are infinitesimal as the whole system is in free fall. Thus, the stimulation of the otolith organs is much less complex. There is some data from parabolic aircraft flights and space missions suggesting that the worst negative effect seen in ground studies, motion sickness up to and including vomiting, does not occur in an otherwise weightless environment, or is at least radically less severe.

In the rest of this paper we will examine the literature to discuss the reasons for artificial gravity and the support for the recommendations. We will also examine the secondary problem of adapting to changing rotation radii as people move between the rim and the axis of rotation.

## Why Artificial Gravity? Health Deterioration in Micro-g

In the early days of planning and designing for space habitation – before there was any real experience to draw from – there was considerable doubt whether humans could survive more than a few hours in weightlessness. Visionaries such as Konstantin Tsiolkovsky, Hermann Oberth, Hermann Noordung, Wernher von Braun, and Willy Ley took it for granted that space stations would rotate to create artificial gravity. Weightlessness was seen as an inconvenient curiosity, not a mission objective. Well into the 1960s, artificial gravity was a major determinant of form in space station studies by NASA and others. See, for example, [Gilruth 1969], [Logsdon 1985], and [Normyle 1969].

Eventually, forays into weightlessness increased in duration, proving that it was not lethal in the short term. With the advent of long-duration missions in Salyut, Skylab, Mir, and the International Space Station (ISS), we've learned that humans can survive more than a year in free fall. Ironically, the same missions that have shown weightlessness to be survivable have also shown how detrimental it is to human health in the long haul.

Without weight, fluid pressure equalizes and fluid shifts from the feet and legs toward the torso and head, initiating something like a biomechanical cascade failure. There are significant effects on the cardiovascular system – including large changes in heart volume – during the first 48 hours as the body seeks a new equilibrium. But, for the most part, the health decline is chronic rather than acute.

[Hall 1994, 1999] provides a summary description of many of the effects. These are distilled from [Chaffin 1984], [Connors 1985], [Covault 1983], [Cramer 1985], [Dahir 1992], [Diamandis 1987], [Griffin 1978], [Gunby 1986], [Keller 1992], [Marwick 1986], [Merz 1986], [Oberg 1986], [Raymond 1986], [Wickelgren 1988a; 1988b], and [Woodard 1984, 1985].

Briefly, prolonged weightlessness provokes the following:

- fluid redistribution;
- fluid loss;
- electrolyte imbalances;
- cardiovascular changes;
- red blood cell loss;
- muscle damage;
- bone damage;
- hypercalcemia;
- immune system changes and “aging”;
- vertigo and spatial disorientation;
- space adaptation syndrome;
- loss of exercise capacity;
- degraded vision;
- degraded smell and taste;
- weight loss;
- flatulence;
- changes in posture and stature;
- changes in coordination.

Countermeasures thus far have addressed the symptoms in a piecemeal fashion, rather than the underlying cause. For example, high-impact strength training may slow the decline of muscle and bone mass, but it does nothing to mitigate the damage to vision from increased fluid pressure in the eyeballs. Dietary and pharmaceutical countermeasures are fraught with complexity and the risk of unintended side effects – further complicated by the fact that weightlessness itself changes the body’s absorption and reaction to drugs. Adding calcium to the diet to preserve bone structure is not very effective when the bones are leaching out the calcium they already have due to their lack of mechanical stress. (On Earth, that stress triggers a piezoelectric effect that regulates the growth of bone where it’s needed [Chaffin 1984], [Mohler 1962], [Woodard 1984].) On the contrary, calcium supplements are likely to increase the concentration of calcium in the blood and urinary tract, with a concomitant risk of developing kidney stones.

Artificial gravity via rotation -- centrifugation -- is the only practical countermeasure that addresses the underlying cause, rather than a subset of symptoms, of the health decline due to gravity deprivation. It’s still not known whether some threshold of gravity less than 1 g

would be adequate to stave off the decline. Except for a few hours by a few men on the Lunar surface, there is a dearth of human experience in anything between 0 g and 1 g.

To the extent that a health risk is attributable to gravity deprivation, we don't need to understand the intricate why's and how's to have confidence that restoring gravity will mitigate the risk. Whatever gravity's effects might be, one can travel from Seattle to Sydney knowing that as long as the gravity in each locale is essentially the same there should be no gravity-deprivation illness or injury.

But is artificial gravity really an adequate match for the real thing? Our most widely accepted and fundamental theories of physics suggest that it is. In Newton's Laws of gravitation and motion, as well as in Einstein's Laws of relativity, gravitational mass and inertial mass are equivalent. In a thought experiment, Einstein conjured a man in a chest far from any other mass, but in constant "upward" acceleration. Every experiment the man can perform within the confines of the chest runs exactly as if the chest were suspended motionless in a gravitational field. Einstein concluded that "a gravitational field exists for the man in the chest, despite the fact that there was no such field for the coordinate system first chosen." [Einstein 1961].

The weight that we feel standing on Earth is not directly due to the downward pull of gravity, but rather to the upward push of the floor. Take away the Earth but keep the floor pushing up on us (e.g., with a rocket) accelerating at 9.8 $m/s^2$ and everything in the chest remains the same. On the other hand, keep the Earth and its gravitational field, but remove the upward push of the floor – as in a drop tube, a plane flying parabolas, or a space station in low Earth orbit – and we experience weightlessness, with all of its unwanted consequences. Evidently, the fundamental force that provides us with healthy stress on Earth's surface is not actually gravity, but rather electromagnetism which conveys mechanical effects from atom to atom within the body. Gravity is not strictly necessary.

We now examine some of the experimental evidence that artificial gravity substantially reduces or eliminates the negative effects of exposure to micro-g.

## Experimental Evidence of the Efficacy of Artificial Gravity

Experiments with artificial gravity on small animals and cell cultures have yielded encouraging results. In the Soviet satellite Cosmos 936 in 1977, the lifespan of rats exposed to centrifugation was significantly greater than that of non-centrifuged control animals. Centrifugation reduced hemolysis[6] and preserved bone minerals, structure, and mechanical properties [Connors 1985]. In Spacelab D-1 in 1985, experiments showed that T-cell function

[6] Hemolysis refers to rupturing of red blood cells.

– which is severely hampered in microgravity – is preserved in artificial gravity via centrifugation [Diamandis, 1987].

On the space shuttle flight STS-90, also known as Neurolab, four crew members were centrifuged during flight with two other crew members acting as controls [Moore 2005]. In the centrifuged astronauts, otolith-ocular reflexes were preserved not only during flight but after landing. The experimental group had normal blood pressure, heart rate and vasoconstrictive variations with tilt when landing, consistent with crew members who fared better on previous landings. The control group had one normal response to tilt and the other did not, consistent with previous flight crews who fared worse on landing.

## Negative Effects of Rotation

Unfortunately, centrifugation is not without its drawbacks. Negative effects of rotation include motion sickness, movement errors, throwing errors and illusions. Motion sickness is by far the most serious for space settlement.

Humans experiencing rotation will sometimes feel motion sickness: fatigue, stomach awareness, nausea and even throwing up. Interestingly, these effects are much smaller when rotating in what is otherwise a micro-g environment (see below for a discussion). Motion sickness during centrifugation is often associated with head motion. Depending on the speed of rotation, distance to the axis of rotation, and Earth's gravity (if present) it can take hours, days, or in extreme cases (for example, at 10 rpm) weeks to adapt to the point that no motion sickness is perceived. The primary motivation of this paper is to find the maximum rotation rate a space settlement can have and yet avoid motion sickness for the residents and, as much as possible, for visitors.

Coriolis forces when rotating can cause limb motion to a target to be inaccurate or to take an unusual path. This is not a debilitating effect and adaptation is fairly quick. Some papers suggest that specific training, where a motion is repeated over and over, can lead to very fast adaptation even at high rotation rates (10 or even 23 rpm).

Difficulty in throwing a ball accurately is familiar to anyone who has tried to do this on a merry-go-round (once a ubiquitous playground feature that has all but disappeared). When spinning, throwing a ball to another kid at the other side of the merry-go-round will miss until the thrower adapts by throwing the ball at the position where the other kid *will* be. This effect was studied in some rotation experiments using dart throwing. The effect, however, is not debilitating and people readily adapt. This effect will, of course, play a large role in some sports played in a space settlement. A home team could take advantage of their adaptation to defeat an otherwise much superior team from Earth.

The oculogyral illusion[7] can occur both with rotation and, interestingly, spaceflight. In rotation, the illusion is triggered by head rotation around a different local axis leading to dizziness, etc. John Glenn observed this illusion on his Mercury flight and found it “essentially the same” as what he had experienced while being rotated in the laboratory on the ground [Graybiel 1977]. While useful for measuring adaptation in experiments, this illusion is not a major problem for space settlement.

We now turn our attention to studies of rotation adaptation.

## Rotation Rate Adaptation Studies

A good summary of the results of the many studies on rotation tolerance can be found in these two quotes:

[Graybiel 1977]:

> "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."

[Lackner 2003]:

> "sensory-motor adaptation to 10 rpm can be achieved relatively easily and quickly if subjects make the same movement repeatedly. This repetition allows the nervous system to gauge how the Coriolis forces generated by movements in a rotating reference frame are deflecting movement paths and endpoints and to institute corrective adaptations."

Many of the seminal studies in this field drew from a series of experiments by Graybiel and associates using the Pensacola Slow Rotation Room at the Naval Aerospace Medical Research Laboratory (Pensacola, Florida). This room was 4.57 m (15 ft) diameter, 2.1 m (7 ft) high, and could rotate within 2.5% of any desired speed up to 10 rpm [Graybiel 1960]. Subjects could move freely about the room and, in at least some studies, could wear a brace to prevent turning their head, which can cause vertigo. Studies were at many rotation rates and some quite long, up to about two weeks, meaning there was ample time to adapt.

[7] “oculogyral illusion: the apparent motion of an object that is fixed in relation to an observer whose semicircular canals have been stimulated by rotational motion—called also oculogyric illusion,” Merriam Webster.

Other studies were conducted in a centrifuge at the Naval Aviation Medical Acceleration Laboratory (Johnsville, Pennsylvania) and in the Rotating Space Station Simulator at NASA Langley Research Centre (Hampton, Virginia). The NASA Langley simulator included an elaborate suspension system to orient a human subject parallel to the centripetal force and allow them to walk on the cylindrical surface, to better model the experience in an actual space habitat and assess the influence of artificial gravity on human gait.

In 1960 Graybiel published a paper [Graybiel 1960] that set the parameters of the debate for some time to come. It provides some of the first data behind our recommendations for space settlement design. There were five regular subjects and one deaf subject who had lost otolith function. Most of the regular subjects were chosen to be highly resistant to rotation effects and one was more average. The deaf subject had no motion sickness symptoms at any time, suggesting that otolith response is the driver in rotation tolerance. Subjects were tested in two-day runs at five rotation rates. They were given a number of tests to complete, but there was no adaptation procedure.

The results of this study may be summarized:

- 1.71 rpm: very mild symptoms.
- 2.2 rpm: one subject threw up (he had a history of seasickness) but otherwise similar to 1.71 rpm.
- 3.82 rpm: mild symptoms and subjects adapted within a day; adaptation was longer for the less resistant subject.
- 5.44 rpm: highly stressful (except for the deaf subject) but most adapted in a day or so. Subjects with prior rotation experience did better than those without.
- 10 rpm: highly stressful (except for the deaf subject); subjects could not complete all tasks. There was some adaptation over the two day run.

The subjects experienced a lot of drowsiness and lethargy, particularly at high rpm. There was a gradual reduction of oculogyral illusion, and reappearance when rotation stopped. Nausea, pallor, and vomiting all occurred but the degree and rapidity of adaptation was a surprise. Adaptation began within hours and was mostly complete in one day for mild symptoms, two days for severe symptoms. Random stimulation (head motions) were harder to adapt to than regular and repeated motions, but this was not a focus of the study. Later studies used a regimen of repeated motions to adapt to high rpm. Incidental runs with a wider participant pool showed wide variations in when which symptoms appeared, their relative prominence, and period required after cessation to readapt. Note that the recommendations in this paper for space settlement rotation rates are more-or-less consistent with the findings of this study.

A year after this study, Graybiel's lab published another paper examining symptoms in four more susceptible subjects subjected to two days of rotation at 1 rpm. They saw few and minor effects. "The results show that exposure under the conditions of this experiment to a

constantly rotating environment at one RPM does not handicap the performance of persons, including those with far greater than average susceptibility to canal sickness." [Kennedy 1961].

In a third study at Graybiel's lab, 10 subjects were exposed to rotation that increased in steps of 1 rpm up to a maximum of 10 rpm [Reason 1970]. At each rotation rate subjects repeated a sequence of head and body movements until they adapted. After adapting, subjects were given five minutes rest with the head fixed before proceeding. The axis of rotation was a little more than one meter from the subject's heads. Here are the results from table I of that paper:

TABLE I. NUMBER OF MOVEMENT SEQUENCES PRIOR TO ACHIEVING ADAPTATION CRITERION AT EACH RPM*

| Subject | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 rpm |
|---|---|---|---|---|---|---|---|---|---|---|
| RE | 0 | 1 | 2 | 9 | 10 | 20 | 33 | 64 | 94 | 157 |
| TA | 0 | 2 | 3 | 2 | 3 | 9 | 10 | 5 | 8 | 8 |
| HA | 1 | 2 | 4 | 4 | 7 | 11 | 18 | 34 | 48 | 22 |
| JE | 5 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| HU | 0 | 1 | 2 | 1 | 1 | 2 | 4 | 5 | 6 | 6 |
| DI | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 3 | 4 |
| HE | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 15 | 31 | T†(45) |
| JA | 0 | 0 | 1 | 12 | 6 | T(23) | | | | |
| SY | 8 | 7 | 1 | 1 | 1 | T(10) | | | | |
| WE | 23 | 44 | 33 | 22 | T(225) | | | | | |

*This value represents the total number of movement sequences executed at each rpm less the three movement sequences, eliciting negative sensation, which constituted the adaptation criterion.

†T indicates that rotation was terminated without achieving the adaptation criterion. The figures in parentheses show the number of sequences completed prior to termination.

The two letter strings are the subjects, the numbers at the top are the rotation rate and the numbers in the matrix are the number of movement sequences necessary to adapt to that level of rotation. Note that some subjects never adapted to 5 or 6 rpm but others had little problem even at 10 rpm. Seven of the ten subjects experienced motion sickness at some point, four severe enough to terminate their testing.

In response to a 1969 NASA Request for Proposals (NASA RFP 10-7192), North American Rockwell built a test facility with a radius of 22 m and crew module 3x12 m. This was used for a four rpm study for seven days with four subjects chosen for minimal susceptibility. Subjects

were monitored for a variety of issues and subjected to a battery of psychomotor tests. Two of the subjects had lower scores on these tests for the first two days of rotation but otherwise all the subjects did very well [Diamandis 1987].

These papers suggest that rotation rate should be limited to four rpm, or perhaps six rpm, at least for visitors, and that training may be necessary to avoid the worst effects (motion sickness) at high rpm. However, these studies are quite old; newer studies suggest higher rotation rates are acceptable with a little specific training. While higher rotation rates are probably of little benefit to space settlement, knowing that they are acceptable with the right training gives greater confidence in the lower, 4-6 rpm, rates' suitability.

Four military personnel in flight training were subjected to 10 rpm for 12 days in the Pensacola Slow Rotation Room [Graybiel 1965]. All subjects were nauseous for a few days and experienced fatigue and drowsiness for much longer. Even after 12 days, none of the subjects had fully adapted. However, it was also noted that there was an onboard observer who had spent a great deal of time rotating in the room and had much fewer symptoms than the aviators. This suggests that countermeasures are necessary, not just passive adaptation, to thrive in 10 rpm – at least with a radius of rotation of a few meters. There things stood for many years.

In 1998 [Lackner 1998] summarized a series of experiments that showed that movement adaptation to 10 rpm could occur with training that consisted of specific movements repeated over and over (around 15-25 times) to train the brain for the rotating environment. When subjected to rotation, subjects tasked to move a body part to a target will have problems until adapted. A set of motions was used in this study as the measure of adaptation, rather than motion sickness. It should be noted that for these experiments the subjects were seated in the center of the rotating room so the rotation environment was different and simpler (presumably easier for the brain to adapt) than that of residing in a free-space settlement.

An experiment at MIT tried a very high rotation rate, 23 rpm [Hecht 2002] in what was effectively a rotating bed where the subjects' heads were near the center of rotation and feet radially outward from the head. While subjects adapted for the most part, even after three days adaptation was not complete.

[Lackner 2003] noted that Coriolis forces associated with normal turning and reaching movements on Earth are often larger than those expected for smaller motions in artificial gravity, even at 10 rpm. This may be why the brain is capable of adapting to even very high rpm given proper training.

While it should not be considered definitive, the experiments examined here strongly suggest that rotation rate does not bound free-space settlement size. It may even be possible to adapt to 10 rpm with minimal training which would correspond to a settlement only 9 m in

radius!  It is safe to say that psychological and social issues alone will set a lower-limit settlement size to something quite a bit larger.

## Reduction of Rotational Effects in Micro-g

In the 1970s, SKYLAB experiments with a rotating chair took data before, during, and after flight.  Eight crew members participated (the Commander of SKYLAB 2 did not).  The chair rotated at up to 30 rpm.  Experiments consisted of increasing the rotation in steps with head motions at each step, for a maximum of 150 head motions.  Nausea levels were measured.  All subjects experienced much less nausea in micro-g, as opposed to pre and post flight in 1g.  On the ground many of the subjects could not complete the 150 head motions, but in orbit all did with few or, in most cases, no symptoms  [Graybiel 1977].

[DiZio 1987] noted that in parabolic flights, where short periods (~30 sec) of alternating micro-g and 1.8g  are available experimentally, nausea caused by head motions in a rotating environment is positively correlated with g-level, with much less nausea at 0g (descending phase of parabolic flight) and heightened susceptibility at 1.8 g (during the pull-up phase of parabolic flight).

This effect, a large reduction in rotation induced motion sickness in micro-g is very good news for space settlements.  It means that the effects seen in rotating rooms on Earth are quite likely much worse than will be experienced in orbit.  This is particularly important for visitors who may not want to spend much of their stay feeling ill.

## Changing g-level Related Studies

While it is clear from the literature that space settlement residents can adapt to fairly high rotation rates (at least 4-6 rpm), there is another issue.  As residents move towards and away from the radius of rotation, the rotation rate will be constant but the radius of rotation will not.  Also, in the very center of a settlement one will experience weightlessness.  Can residents instantaneously adapt to these different rotation environments?

The short answer is that we don't know, but the literature suggests that this may not be much of a problem. There have been a number of studies examining intermittent centrifugation to counteract the negative effects of weightlessness and these studies provide some evidence for dual-adaptation, i.e., that with some exposure no adaptation time is necessary when transitioning from a rotating to a non-rotating environment.  Also, in some of the rotation studies, experiment observers repeatedly moved in and out of rotating rooms and, with experience, could do so without problem.

[Graybiel 1965] exposed four aviators to 10 rpm for 12 days. There was also an onboard observer who entered and left the room frequently. This individual had no problem going back and forth between a rotating and nonrotating environment.

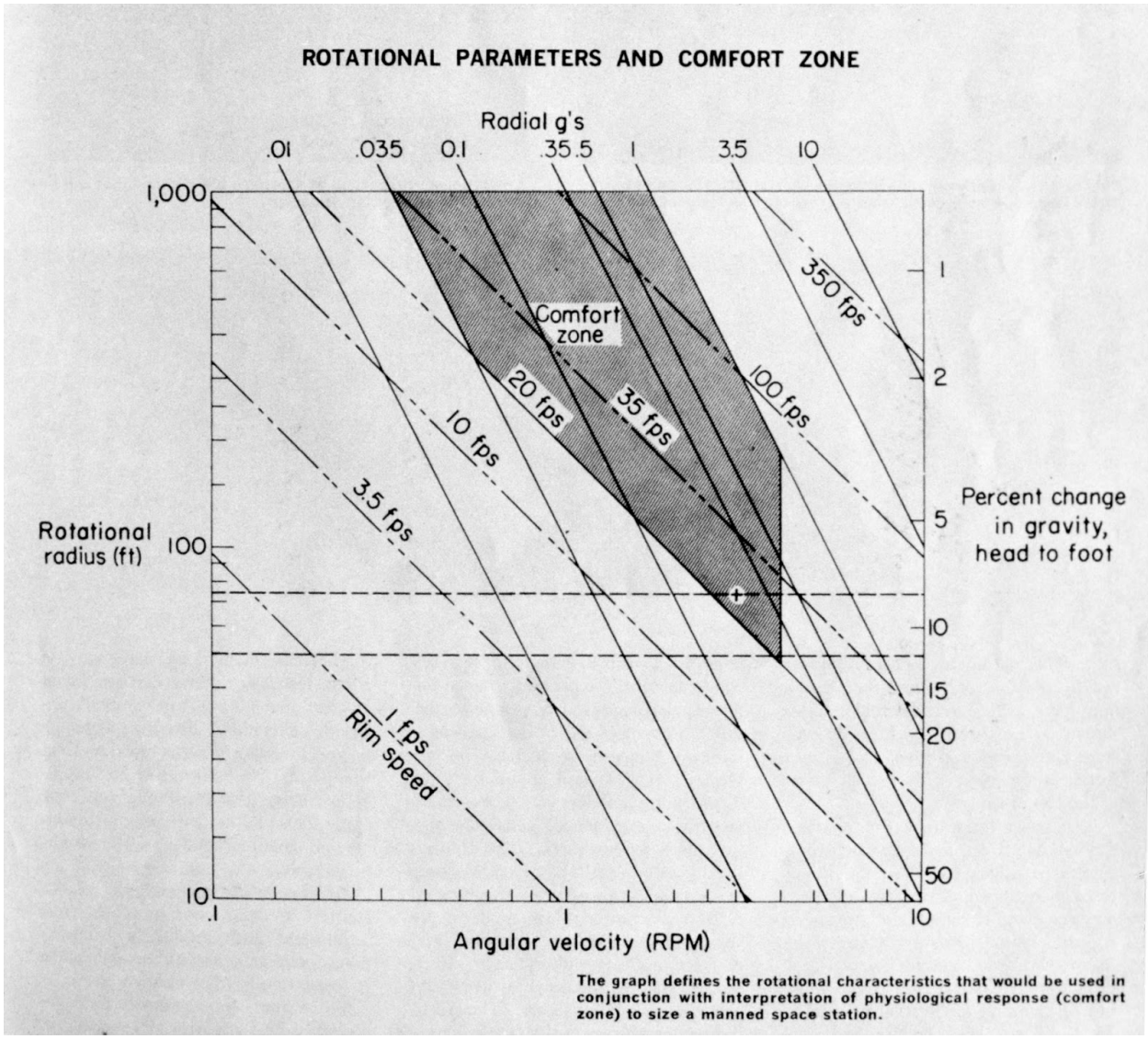
[Hecht 2002] noted that subjects maintained their adaptation to a stationary environment even while (mostly) adapting to 23 rpm over three days.

Transiting to and from the axis of rotation is somewhat different. Although the centripetal acceleration – the "nominal gravity" – goes to zero g in proportion to the radius, the rotation rate remains constant. The biggest factor affecting the comfort and ease of adaptation is likely to be the design of the ladder or elevator. If the rate of climb along the radius is constant, then the Coriolis acceleration also remains constant and becomes an ever greater proportion of the total acceleration. Near the axis, the acceleration is nearly all Coriolis. For a radial ladder or elevator, the Coriolis acceleration is tangential – perpendicular to the centripetal – and distorts the sense of vertical. The design to accommodate the Coriolis acceleration and associated force requires attention to detail, but does not appear to be an insurmountable problem.

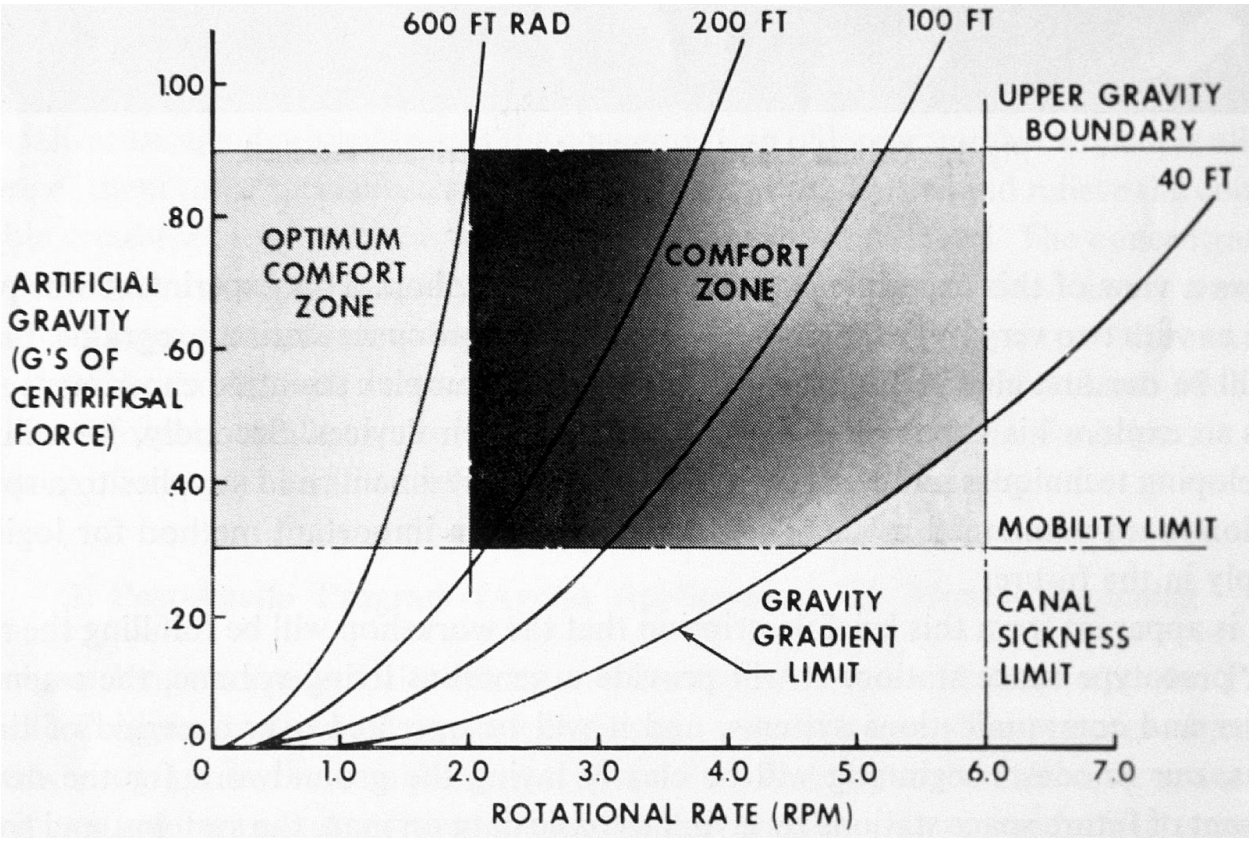
In regard to the rotation rate and outer rim radius, other authors have attempted to synthesize the literature and give recommendations as to acceptable limits. In this next section we examine some of these.

## Comfort in a Rotating Environment

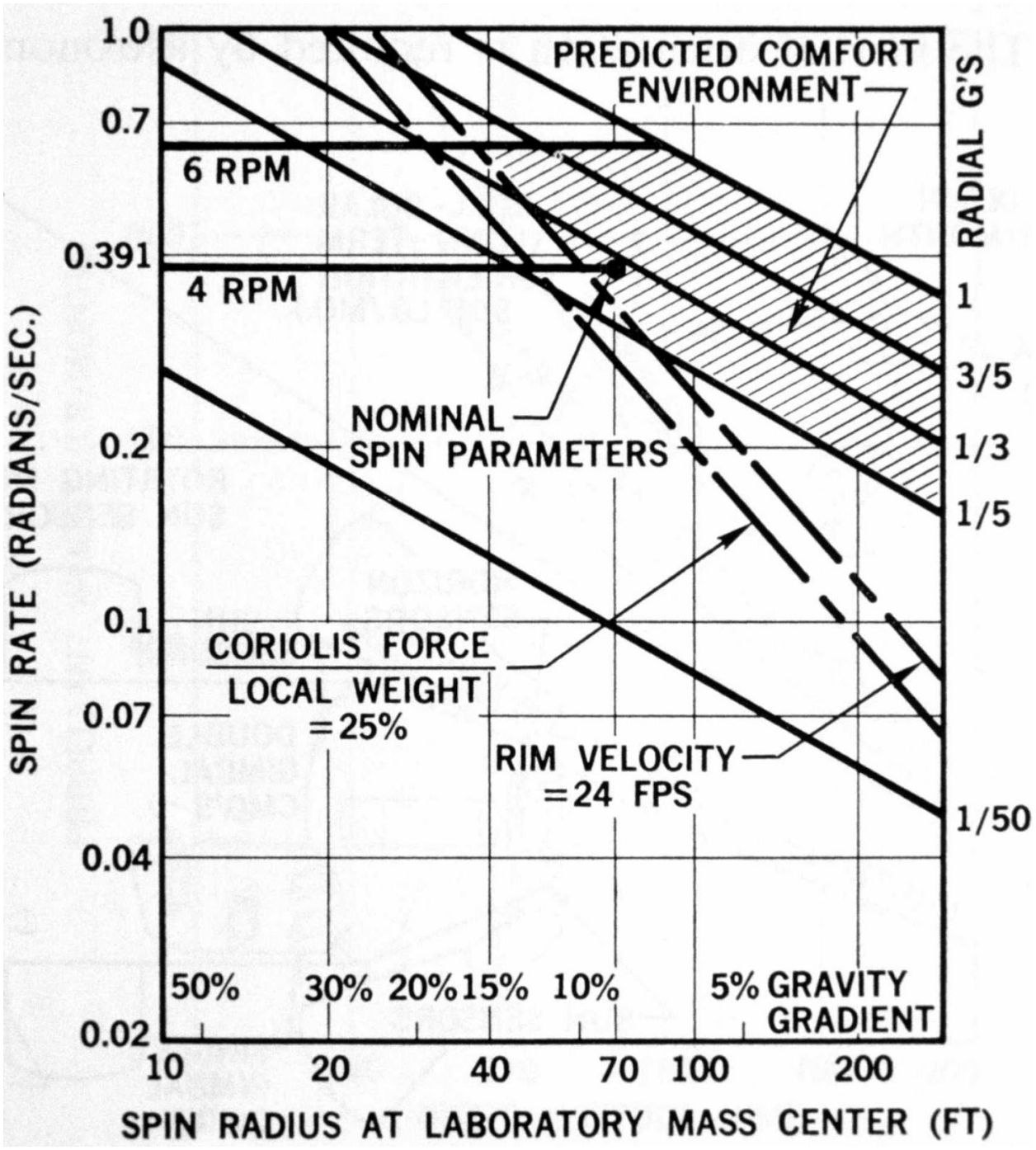
Based on the studies summarized above and others, there have been various attempts to draw definitive conclusions about comfort in artificial gravity at different rotation rates, radii and g-levels. Various authors have presented comfort charts to delineate acceptable values for radius, spin rate, centripetal acceleration, and tangential speed. The problem these authors addressed was more complex than ours in that they were interested in more than a single g-level, whereas this paper is only concerned with producing 1g. Five of these attempts to define the artificial gravity comfort zone are shown below. Note that they are not in agreement, but for 1g they are more-or-less in the range of rotation rates recommended by this paper.



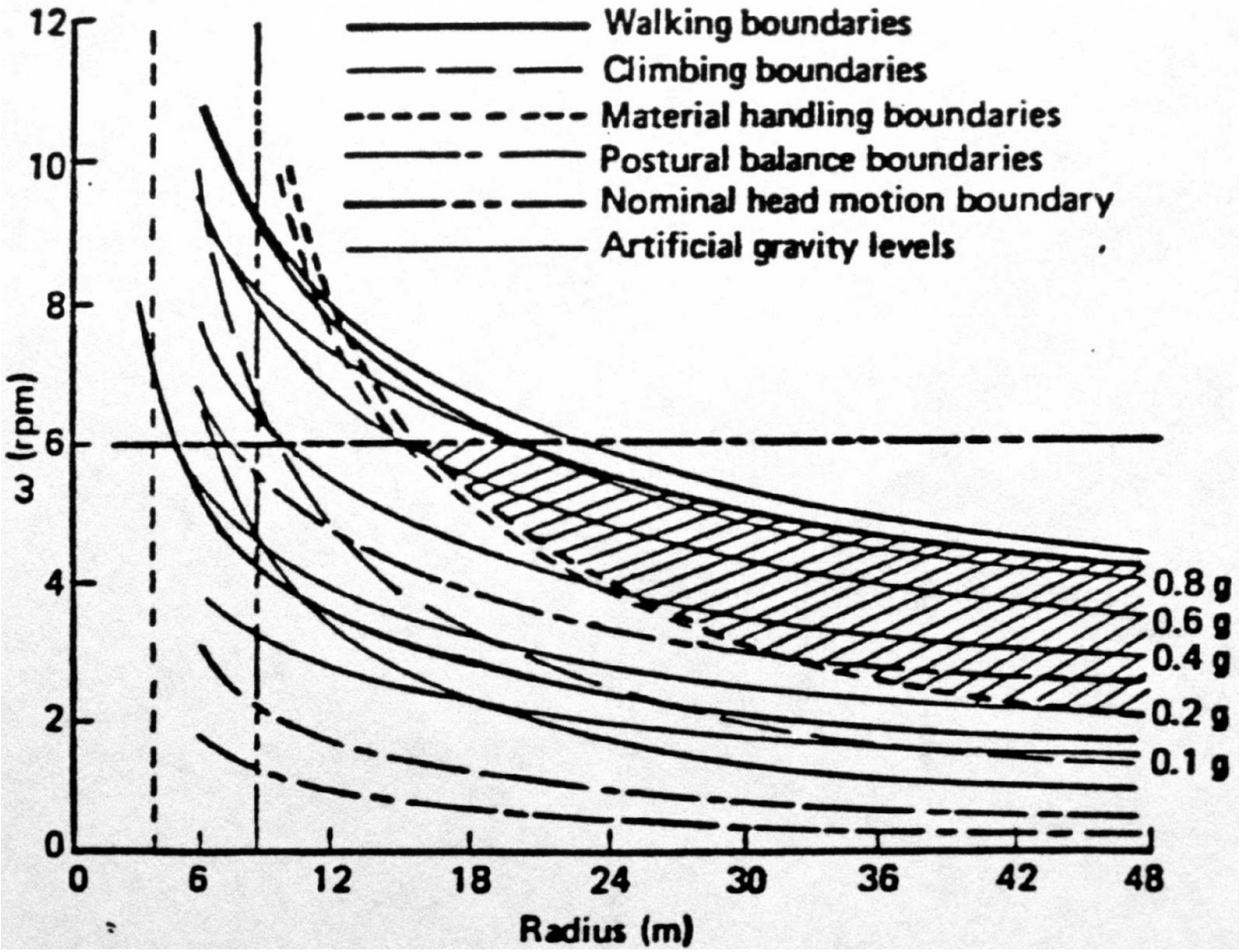

Comfort chart, [Hill 1962]. At 1g this chart suggests that rates up to 4 rpm are in the comfort zone. (Note that, between 1 and 2 rpm, and between 2 and 3, there are intermediate tick marks corresponding to approximately 1.5 and 2.5.)



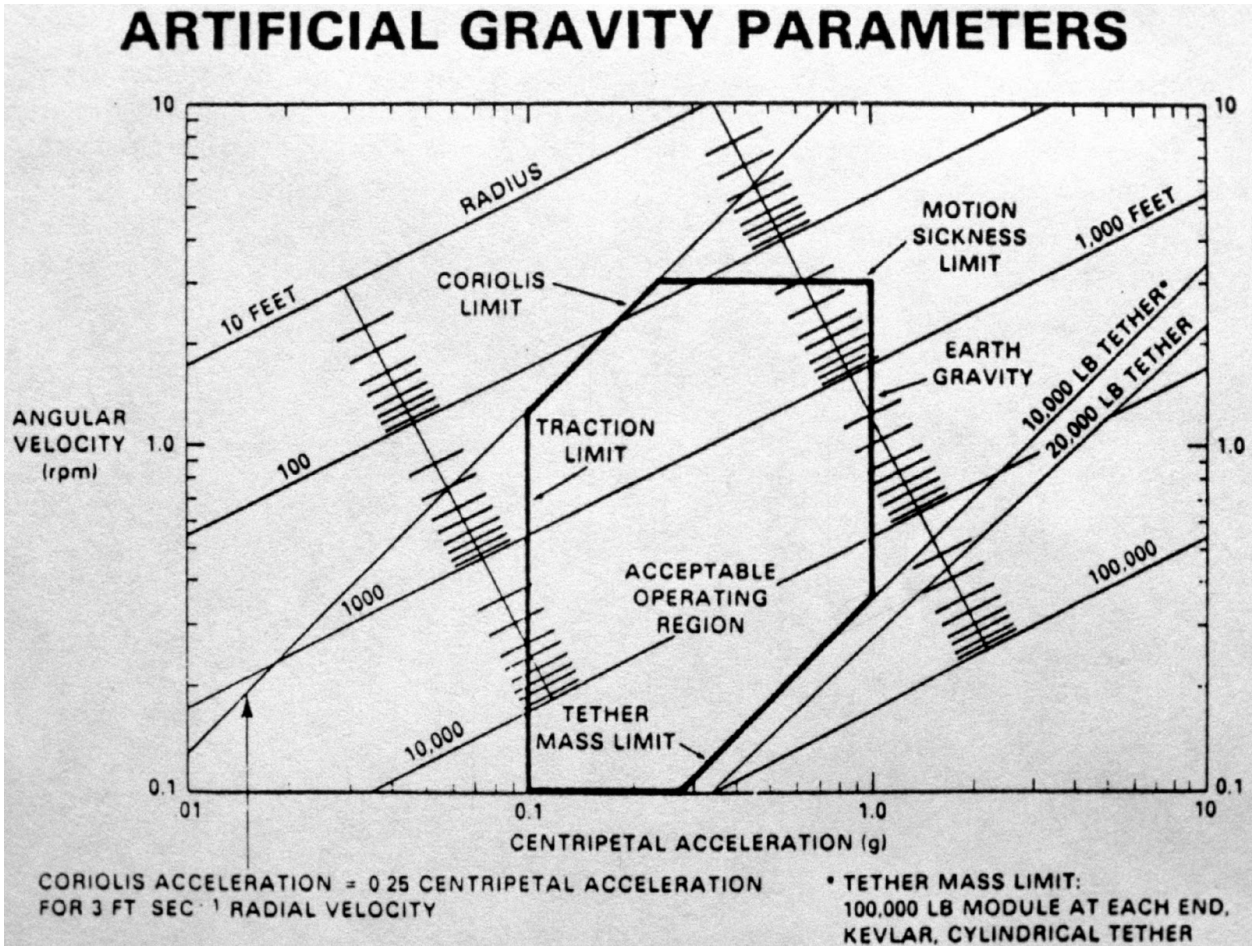

Comfort chart, [Gilruth 1969]. Here 6 rpm is the chosen limit to comfort.




Comfort chart, [Gordon 1969]. Here 6 rpm is the limit of comfort at 1g.



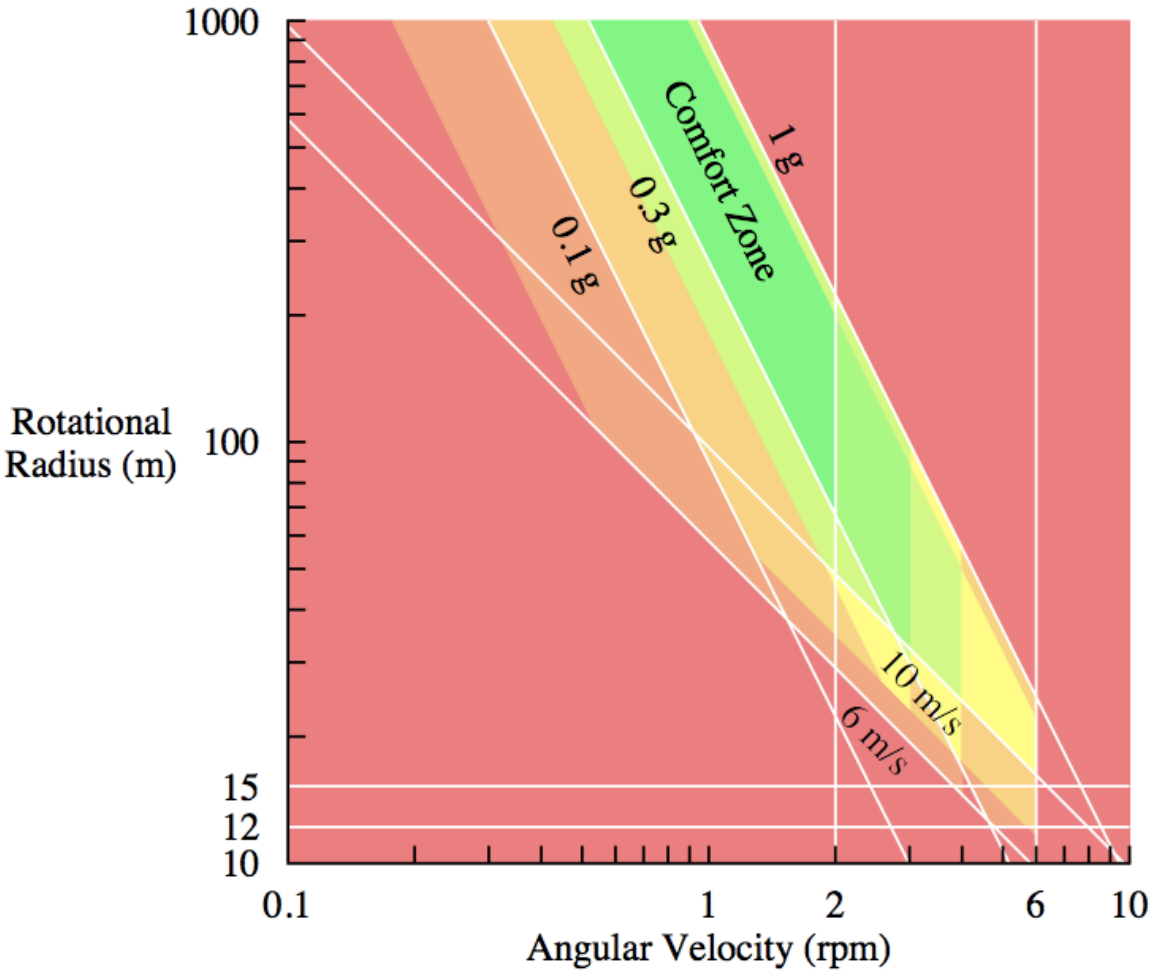
Comfort chart, [Stone 1973]. Again, 6 rpm is the limit of comfort.



Comfort chart, Cramer, 1983. Here 3 rpm is the motion sickness limit.

It is clear that there is only rough agreement between these charts, but with one exception [Cramer 1983] they are more-or-less in line with the recommendations of this paper. Interestingly, the Hill and Schnitzer chart from 1962 is particularly oft-cited in the literature. If it was the only chart one ever saw, one might be forgiven for taking its comfort boundaries as firm and definitive. Only by comparing with alternative charts do the uncertainties become apparent. Unfortunately, the inconsistent formats mask the inconsistency in the proposed comfort boundaries themselves.

To synthesize the recommendations of these authors, the following figure charts all of them in a consistent format (following the style of [Hill 1962]), and colors the regions according to the number of “votes” for comfort. Regions that all consider comfortable are green; regions that all consider uncomfortable are red; regions of disagreement are colored in intermediate shades of yellow and orange.




The greatest disagreement occurs in the area of high angular velocity and small radius. However, the extreme condition might be too small to be relevant for a settlement-sized structure. At 1g acceleration these combined data show that 2 rpm is universally agreed to be good, and up to 4 or even 6 rpm is accepted by most, in line with our recommendations.

## Discussion and Consequence

### Interpreting the Results

One must be careful in assessing the results presented here. First, these are small studies with few individuals and very limited rotation times. Second, there is what's known as the Hawthorne Effect, where people perform better when they know they are observed, as all of the subjects in these studies were. Third, there is lack of agreement in the literature noted in the last section.

However, considering that residents of a space settlement will almost always be at much greater distances from the center of rotation relative to the data underlying the comfort zone estimates, and the studies that suggest simple training routines provide tolerance of 10 or even 23 rpm, and the evidence that rotation of a system in micro-g is much less detrimental than on the Earth's surface, there is considerable confidence that space settlements can rotate up to 4 or maybe even 6 rpm without great difficulty. This translates into a system size of around 25-56 m radius, far smaller than previous designs which assumed 1-2 rpm (225-900 m radius).

## Implications for Early Space Settlement Construction

One of the tallest poles in free space settlement construction is simply bringing all the necessary materials to the correct location. Thus, the mass of a settlement is a fairly good indicator of the difficulty of building the settlement. We now examine the implications of our rotation tolerance finding on the mass of the first space settlement.

As the radius of a space settlement design shrinks, some of the mass scales by the square of the radius, and some by the cube. Specifically, in a spherical settlement, the mass of

- the atmosphere scales as the cube as it is proportional to the volume.
- the hull scales as the cube, since the hull surface area scales as the square and pressure vessel stress and thus hull thickness scales linearly.
- radiation shielding scales as the square, since it is on the hull surface.
- internal furnishings will tend to scale as the surface area and thus as the square.

The radius of a 1g rotating environment scales as inverse square of the rotation rate. Thus, doubling the rotation rate (e.g., from 2 to 4 rpm) reduces the radius by a factor of 4. Thus going from 2 to 4 rpm the total mass of the settlement will be reduced by a factor of 16-64. This is a huge reduction, and it is synergistic with another recent finding.

Using NASA's OLTARIS radiation modelling software, [Globus 2015] found that space settlements in equatorial orbit below about a 500 km circular orbit may not require radiation shielding. The Earth itself and the Earth's magnetic field appear to provide sufficient protection assuming 20 mSv/year for the general population and 6.7 mGy/year for pregnant women radiation limits. Since the mass of settlements in high orbits is dominated by radiation shielding, eliminating the shielding reduces the mass of typical settlement designs by a factor of about 19 to over 2,000[8] [Johnson 1975 tables 4.1 and 4.2]. See the following table.

[8] The factor of 19 is for a cylindrical settlement; it is 2,333 for a dumbbell. These represent the extremes in volume vs surface area (which must be covered with shielding in these designs. See http://settlement.arc.nasa.gov/75SummerStudy/Chapt4.html#Shielding for the tables this is based on -- tables 4.1 and 4.2.

| Mass model basis [Johnson 1975] | | mass in tons | | |
|---|---|---|---|---|
| shape | structure | atmosphere | shielding | total/non-shielding |
| multiple dumbbells | 75,000 | 37,000 | 9,900,000 | 89 |
| multiple torus | 100,000 | 10,400 | 9,700,000 | 89 |
| banded torus | 112,000 | 13,200 | 7,000,000 | 57 |
| single torus | 4,600 | 1,900 | 1,000,000 | 155 |
| cylinder | 775,000 | 299,000 | 19,400,000 | 19 |
| sphere | 64,600 | 35,200 | 3,300,000 | 34 |
| dumbbell | 400 | 200 | 1,400,000 | 2,334 |

In this table the rows are settlement shapes. The second through fourth columns are the mass of various parts of the settlements in tons. Note that the mass of internal furnishings is not estimated. The last column is the ratio of the total mass divided by the structure and atmospheric mass.

Assuming the most conservative reduction numbers for faster rotation (16) and eliminating shielding (19), a 4 rpm settlement in equatorial orbit LEO (Low Earth Orbit) with no radiation shielding may be about 16 x 19 = 304 times less massive than projected for earlier space settlement designs. However, if interior furnishings were included this figure would probably be lower.

Even if this estimate is quite optimistic, this is still a massive reduction in the quantity of materials necessary to build the first space settlement. Because the early designs were so massive, being large and requiring radiation shielding of around 4.5 tons per square meter of hull, it has always been assumed that lunar and/or asteroidal materials would be necessary to build the first space settlement. This means developing mining operations and a whole transportation architecture before the first settlement can be built.

However, if further examination proves these mass models to be even close to accurate, then building the first settlement in equatorial LEO saves 99+% of the mass of the system. This may mean that the materials can simply be launched from Earth, particularly if current efforts to develop operational reusable launch vehicles are successful. This would radically simplify construction and significantly advance the day when the first space settlement is built.

Furthermore, the size of a 4 rpm settlement, ~112 m diameter, is about the same as the long axis of the International Space Station (ISS, ~108 m) which is already in orbit. Subsequent stations and space hotels in the not too distant future could easily begin to approach the size of a 6 or even 4 rpm space settlement, providing an incremental path to the first true space settlements. This path consists of small steps as new human occupied space systems are developed for science, manufacturing, tourism, and even perhaps low-g retirement homes [Globus 2012].

It is too soon to be certain that this approach will truly eliminate the need for extraterrestrial materials to build the first settlements and, of course, extraterrestrial mining and materials transport will be necessary to settlement outside of equatorial LEO. However, our rotation findings lead to a tantalizing glimpse of a viable path to our first permanent, if rather small, home in space. More and larger settlements will, one hopes, surely follow.

## The Next Step

While the results of this paper are encouraging they are far from definitive. Before committing to building 4 to 6 rpm settlements a great deal more research is in order. Therefore, it would be wise to begin a research program focussed on understanding human response to living in rotating environments comparable to space settlements.

Note that the artificial gravity requirements for long duration space missions are much different. Missions to, say, Mars

- are only a few years long,
- involve only adults,
- may be able to accept sub-1g levels,
- have severe constraints on the size of the vehicle.

Settlements, by contrast,

- expose residents for decades,
- involve children as well as adults,
- have 1g as a hard requirement,
- can be much larger than ships traveling to and from distant destinations.

Thus, a program aimed at mitigating the negative effects of long duration space missions may be quite different from that aimed at enabling space settlement. However, both research directions involve understanding the same biological systems and their response to the same sort of environment. Therefore, it is reasonable to expect that studies aimed at using artificial gravity in long duration space missions may be quite useful for reducing the uncertainties related to human response to space settlement rotation rates, although a program focussed directly on settlement would be preferable.

## Conclusions

While the data are not definitive, a survey of the literature strongly suggests that free-space settlements can provide comfortable 1g artificial gravity by rotating at up to 4 or even 6 rpm. This implies a radical reduction in the minimum size and thus mass for the first space settlements relative to older designs. Combined with eliminating the radiation shielding mass needed in high orbit, which is acceptable in equatorial LEO, this may lead to a two orders of magnitude reduction in free-space settlement mass.

There are significant uncertainties in our rotation rate tolerance conclusions due to the small sample sizes in the relevant studies, the use of very small centrifuges, and the complexity of adapting to rotation when on the surface of the Earth and subject to its gravitational field. Most of these uncertainties, when resolved, can be reasonably expected to allow even greater rotation rates. Thus, the minimum size for space settlements does not appear to be set by the rotation rate necessary to achieve 1g artificial gravity.

With smaller radius, lower tangential velocity, and higher angular velocity, Coriolis acceleration become increasingly significant. The smaller settlements proposed here will be most likely to succeed if designers remain vigilant of the effects and take appropriate measures in planning activities and motion paths.

So what is the smallest a space settlement can be? We don't know yet, but it is probably at least 50 m diameter, the size of a 6 rpm settlement. Other factors, perhaps psychological, social or environmental stability, may well dictate a somewhat larger systems. In any case, the huge spacecraft necessary to achieve 1 g with no more than 1 or 2 rpm are not necessary, and that brings space settlement much closer to reality.

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