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DETERMINANTS OF ORIENTATION IN MICROGRAVITY

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ABSTRACT

During two parabolic flight campaigns, one with the NASA-KC-135, the second with the ESA-Caravelle, human spatial orientation in an altered gravitational environment was studied by measuring the subjective visual vertical (SVV) by means of a luminous line, and by asking the subjects to give a report, with eyes closed, about their orientation to apparent vertical. The inflight data are compared with baseline data measurements of the subjective horizontal body position (SHP) at normogravity (1*g*) and at 2*g*.

Pertinent theoretical alternatives to modelling subjective static orientation are developed and compared to the data. It turns out that a good fit to the baseline results and a satisfactory prediction of the perceived orientation in microgravity can be obtained if the otolithic output is assumed to be normalized, but that of the somatic gravity sensors is not.

1. INTRODUCTION

In weightlessness most subjects experience a definite, idiosyncratic orientation with respect to the vertical rather than indifference. This can be found also in the short period of microgravity of parabolic flight[1]. Obviously, information about orientation cannot then be provided by shear forces on the otoliths; hence the actual experience is supposed to be based on gravity-independent parameters[4,6,8].

The perceived direction of "up", the subjective visual vertical (SVV), was measured by means of a luminous line in the three gravity states of parabolic flight. Additionally the subjects (Ss) were asked to report their perception of body position in microgravity. These results are compared with baseline measurements of the subjective horizontal body position (SHP) on the tiltable board and on the human centrifuge.

2. EXPERIMENTAL SETUP

2.1 Parabolic flight

During parabolic flight (for acceleration profile see lower part of Figure 2) the illusions of feeling upright or upside down (the latter is called "inversion illusion") were quantified by measuring the perceived direction of "up" by means of a luminous display.

In the test paradigm the S was placed in a right or left side down position on the floor of the airplane, slightly restrained by safety belts to prevent uncontrolled free-floating during the zero *g* phase. Their visual axis was parallel to the flight direction of the airplane.

For indicating the SVV we used a luminous line, which was geometrically polarized by a luminous disk at one end, such that it looked like a pendulum. The luminous line was a LED display mounted within a modified diving goggle, connected to a motor unit, and rotatable by remote control. The Ss were asked to keep the "pendulum" perpetually vertical during the experiment. The rotation angle of the display and the outputs of a 3-axial accelerometer mounted near the head of the subject were recorded.

Ss were placed parallel to the floor rather than (as usually) normal to it, because in the latter case the SVV coincides with the oculo- or headcentric Z-axis at 1*g* and hence might be confounded with these gravity-independent positions upon entering 0*g*. In our chosen case, however, the luminous line is far from the Z-axis at the critical moment (see also Figure 2), and should then appear clearly askew to an SVV which then, at 0*g*, is directed towards one's feet or one's head.

The test sequence consisted of setting the luminous line during four parabolas and of voice reports of the perception of body position with the display switched off, that is, under visual occlusion, during one parabola. In the ESA campaign this sequence was performed once lying on the right side (facing towards flight direction) and once on the left (facing against flight direction), in order to evaluate the effect of the small angular accelerations during the parabola.

Fortunately the experiment itself did not seem to be provocative so that all Ss were able to finish the test sequences, even those who suffered of some motion sickness symptoms.

Thirteen Ss participated in the first parabolic flight experiment, nine Ss in the second and two of them in both. Five subjects of the first campaign were unfortunately not able or willing to join our baseline data collections.

Prior to the in-flight experiment all Ss were instructed about the experiments. But in the first campaign, a NASA KC-135 flight, several participants had no prior experience in psychophysical experiments and therefore appeared to have problems in understanding their task. Thus in the second campaign all of the subjects had at least to perform some SVV settings as a training. The following will mainly refer to this second campaign.

2.2 Baseline data

Baseline data collection consisted predominantly of measurements of the subjective horizontal body position (SHP). Table I gives an overview of inflight and baseline data of the Ss participating in most experiments. The S, lying right side down on a tiltable board, had to move this board by remote control until he/she feels horizontal. The test was performed in darkness without any visual cues and repeated 12 or 16 times (see also Mittelstaedt[7]).

Also a similar experiment in a human gondola centrifuge was realized for one S of the first and eight Ss of the second campaign to determine the SHP during 2*g*. One of them was not able to finish this test properly; he wanted to adjust himself at an angle beyond the mechanically possible values (see Table I, data in brackets).

In addition most of the Ss did the same task on the sled-centrifuge of the institute (see Figure 1). With this experiment it has been able to prove the existence of a second gravity system in the trunk[11]. When the centrifuge rotates, additionally to the gravity vector a second linear acceleration, the centrifugal acceleration, acts on the subject. Then the addition of both vectors is interpreted as gravity. The Ss task is again to put themselves in the horizontal position by moving the sled over the centrifuge platform. Supposing that only the vestibular system can measure linear accelerations, the subject should now move the sled until the force acting upon the otoliths is the same as on the tiltable board. For a S which sets the board objectively horizontal, this is the case when the vestibular system of the subject is in line with the axis of the centrifuge as shown in Figure 1. But the subjects feel subjectively horizontal if the centrifuge axis is shifted towards their feet by a distance d_v between labyrinth and

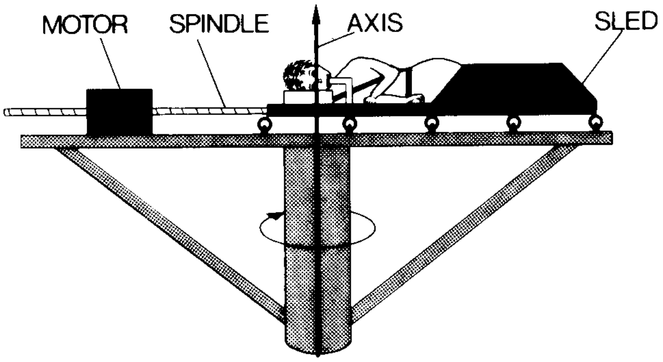

Fig.1 Sled-centrifuge of the MPIV Seewiesen (after Mittelstaedt & Fricke[11])

centrifuge axis which varies between 0 and -52cm . If the baseline SHP is allowed for, a control sample of 21 Ss evinced a mean d_v of -26±11cm (see also data in Table I). Therefore additional gravity receptors must exist in the trunk (for their location and function cf. Mittelstaedt, in press[10]).

3. RESULTS

3.1 Baseline data

The baseline data are shown in the 3 right side columns of table I. Almost all Ss are objectively in a head-up posture when they feel to be horizontal; and this changes little, by idiosyncratic amounts and signs, at 2*g*. At the sled-centrifuge all Ss show a large deviation from what is expected with exclusive otolithic control of the SHP. The results will be discussed in section 4 (theory) below.

3.2 Static flight data

Since preflight training was more extensive and more baseline data are available for the ESA flight, data evaluation will be mainly restricted to this campaign.

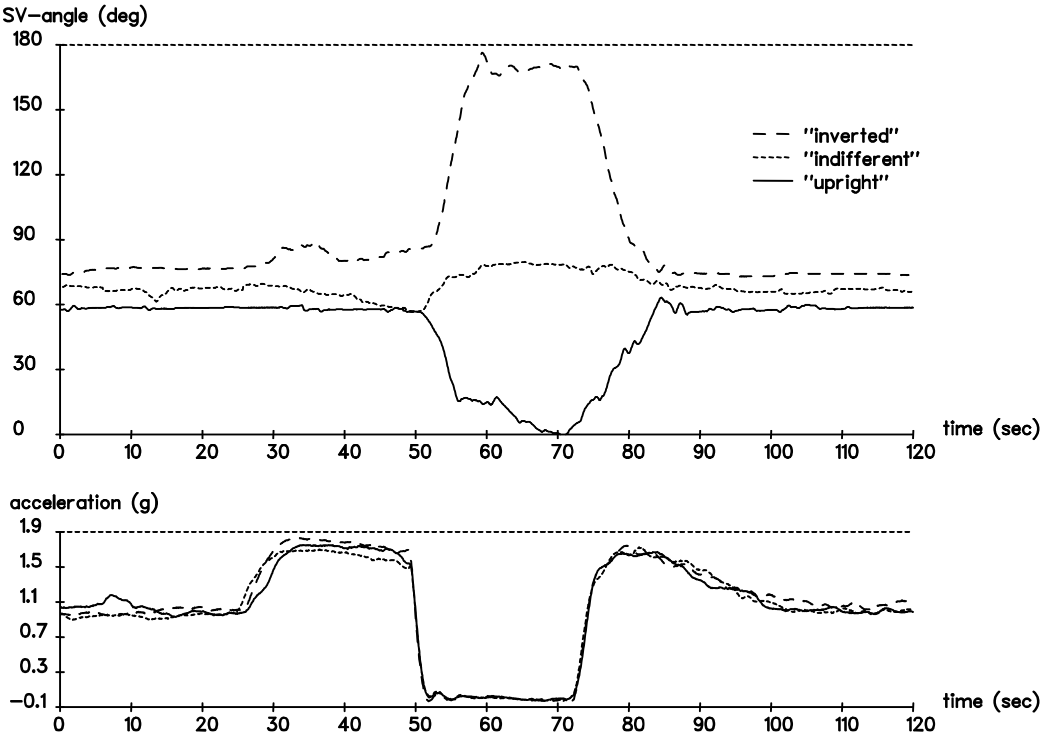

Fig.2 Three examples of visual SV time courses (means of 8 parabola). Lower part : acceleration profile (head-Y-axis)

The upper part of Figure 2 shows 3 examples of the time course of SVV settings over the acceleration profile of the plane in the lower part. They have been selected to illustrate typical modes of SVV settings during 0*g*. The modes are classified as "upright", "inverted" and "indifferent", respectively. Table II shows the number of Ss in each mode for both campaigns.

The reports about body position in darkness gave the following results : The reports of the "indifferent" Ss were consistent with their SVV setting. The inversion illusion of one of the Ss, however, depended somewhat on the tightness of the safety belts. Remarkably, three of the visually "upright" Ss reported an "inverted" body position. If is well known that SVV and SHP are based on different, only partially overlapping inputs[4] and hence may differ in identical orientations. We shall come back to this issue in section 4 and 5 below.

Table I Parabolic flight data (from voice recordings) and baseline data (subjective horizontal position, in brackets: invalid data)

Subject	Parabolic flight	Baseline (SHP)		
	body position, eyes closed	sled-centrifuge	Gondola-centrifuge 1*g*	Gondola-centrifuge 2*g*
A	"head down 20°-30°"	-5.32±1.08cm	61.6°±1.0°	66.1°±2.4°
B	"slightly head down"	-2.34±0.58cm	65.9°±4.0°	72.9°±1.1°
C	"slightly down, maybe 20°-30°"	- - -	95.0°±1.5°	(100.2°±1.8°)
D	"slowly feeling upside down"	- - -	70.0°±1.2°	70.2°±1.2°
E	"really upright"	- - -	76.8°±1.4°	78.7°±2.4°
F	"really on the feet"	-36.68±1.79cm	87.9°±1.9°	80.4°±1.5°
G	"perfectly 180°"	-29.13±2.17cm	86.9°±2.5°	95.2°±2.5°
H	"head down, directly to ground"	-5.72±1.82cm	73.2°±1.9°	66.3°±1.2°
J	"clearly upside down"	-29.53±1.59cm	87.0°±1.5°	87.0°±1.6°

3.3 Dynamic flight data

Not only the static perception of the SVV and the body position can lead to different values but also the dynamics are not always corresponding.

The static values of the SVV were computed from the time course as the mean of the SVV settings of every *g* phase without the first 10 sec to avoid the influence of transition from one phase to the next. This transition was analyzed by fitting exponential functions to the first 20 sec of the zero *g* phase and of the following 2 *g* phase.

Comparison of the zero *g* SVV values facing towards and against flight direction reveals no significant difference for 8 of the 9 subjects. Thus it can be stated that the weak angular accelerations had no influence on the experimental results.

Table II Classification of SV-settings in both parabolic flight campaigns

	NASA-KC135	ESA-Caravelle
Number of Ss	13	9
"indifferent"	9	4
"upright"	2	4
"inverted"	2	1

Most Ss reached the final value of the SVV in weightlessness within the first 10 sec and corrected their settings only little in the last 10 or 12 sec.

The mean time constant derived by fitting exponential functions to the SVV time course was 8.50±3.2 sec. This dynamic behavior of the SVV is not consistent with other experimental findings in a changing gravitational background like the "oculogravic illusion"[2], which evinces a time constant of about 20 sec. Furthermore the mean time constant from 0*g* back to 1.8*g* was significantly shorter (4.31±2.49 sec) than that for entering zero g.

This shows that the time constant of the SVV is influenced by the momentary amount of gravity and probably by the preceding time course of the acceleration.

4. THEORY

For an interpretation of the experimental findings during microgravity with respect to the baseline data some theoretical considerations are necessary. Several different mathematical formulations modelling the static phenomena of human orientation will be developed and discussed.

4.1 A fairly straightforward explanation rests on the simple assumption that the S tries to null the sum of the Z-components of measured linear acceleration when adjusting the SHP.

The evaluation of this Z-component depends on vestibular as well as somatic inputs. The vestibular information processing starts with summation of the afferent discharge rates of the otoliths according to the direction of polarization of the receptor cells with respect to the head's Z-axis. This yields an input variable which is proportional to the Z-component of the gravito-inertial force vector. It originates mainly from the saccule and consists of a bias discharge rate S_0 and an amplitude factor S_1. The somatic part is composed of a respective somatic bias B_0 and an amplitude factor B_1. It is assumed that the S, when asked to orient horizontally, rotates the board or shifts the sled until the sum r of these two variables is zero, that is, feels a head-up or head-down deviation from the horizontal corresponding to r

$$r = S_0 + S_1 \cdot z + B_0 + B_1 \cdot z = 0 \tag{1}$$

z is the Z-axis force vector component acting on the somatic and otolith systems, i.e. z is equal to $g$cos? on the board and to d_v?^{2}/981 cm sec^{-2} on the centrifuge. If the sums of the resting discharges, here called B_0 and S_0, are not zero, the subject will at zero g perceive a head-up or head-down deviation r from the horizontal, corresponding to the sign and amount of the sum of receptor biases:

$$r_0 = S_0 + B_0 \tag{2}$$

According to equation (1) the sign of the joint bias can be inferred from the tiltable board experiment at 1g alone :

$$\frac{S_0 + B_0}{S_1 + B_1} = -\,g \cdot \cos\rho \Rightarrow if\ \ \rho > 90° \quad then\ S_0 + S_1 > 0 \tag{3}$$

Therefore a S with SHP larger than $|90°|$ should experience a head-down deviation from the horizontal in zero g. Quantitatively the bias (r_0) would be much smaller than the value of r at an inverted position at normogravity however. This hypothesis gives also a straightforward prediction for the SHP at 2g:

$$\frac{S_0 + B_0}{S_1 + B_1} = -\,g \cdot \cos\rho \rightarrow \cos\rho_{1g} = 2\cos\rho_{2g} \rightarrow \rho_{2g} \approx (\rho_{1g} + 90°)/2 \tag{4}$$

If for example a S evinces a SHP of 94° at 1g, the 2g value should be about 92°. But none of the eight Ss which participated in our baseline data collection at 1g and 2g behaves as expected from Eq. (4). The often considerable deviations of SHP from ?=90° cannot be caused by the joint bias alone, but point to the intervention of additional influences. They shall be discussed presently.

4.2 The first alternative solution to be considered contends that the SHP is determined by an internal reference, which is idiosyncratic but constant for a given S at the time of all experiments done here. There are essentially two ways to reference setting, component modulation[3,5] or addition.

Assume that the SHP is determined by a reference angle µ, and that the variable r is a sinusoidal function of the difference µ-?. Since the otolithic information is represented in component form, the reference (µ) will also be represented by orthogonal components :

$$r = \sin\mu \cdot [S_0 + B_0 + (S_1 + B_1) g \cos\rho] - \cos\mu \cdot [(U_1 + B_{y1})\, g \sin\rho] = 0 \tag{5}$$

where U_1 is the weighting factor of the utricular information which corresponds to the acceleration y acting in the Y-axis, and B_{y1} the respective somatic amplitude.
Hence, at g=0 :

$$r_0 = (S_0 + B_0) \cdot \sin\mu \tag{6}$$

In our case, µ is positive, and ranges between 60 and 90 degrees.
Because

$$\tan\mu = \frac{(U_1 + B_{y1}) \sin\rho_{1g}}{S_0 + B_0 + (S_1 + B_1)\cos\rho_{1g}} = \frac{(U_1 + B_{y1}) \sin\rho_{2g}}{S_0 + B_0 + 2(S_1 + B_1)\cos\rho_{2g}} \tag{7}$$

it follows directly that

$$\frac{S_0 + B_0}{S_1 + B_1} = \frac{2\sin(\rho_{1g} - \rho_{2g})}{2\sin\rho_{2g} - \sin\rho_{1g}} \tag{8}$$

Because in our case ?$_{2g}$>30°, it follows that S_0+B_0>0 if ?$_{2g}$<?$_{1g}$.

4.3 A very similar relation ensues if an internal reference A is added to a normalized tilt variable r. Assume that

$$r = A + \frac{S_0 + B_0 + (S_1 + B_1)\, g \cos\rho}{\sqrt{[S_0 + B_0 + (S_1 + B_1)\, g \cos\rho]^2 + [(U_1 + B_{y1})\, g \sin\rho]^2}} = A + \frac{\tilde{z}}{\sqrt{\tilde{z}^2 + \tilde{y}^2}} \tag{9}$$

hence, at g=0 :

$$r_0 = \frac{S_0 + B_0}{|(S_0 + B_0)|} + A \tag{10}$$

In our case, since A<1, r_0 is entirely determined by the sign of (S_0+B_0). If A is zero, we obtain the same relations at 2g and 1g and 0g as in Eqs. (1) to (4). However, if $A \neq 0$, idiosyncratic and constant, it follows directly from Eq. (9) that

$$A = \frac{\tilde{z}_{1g}}{\sqrt{\tilde{z}_{1g}^{\,2} + \tilde{y}_{1g}^{\,2}}} = \frac{\tilde{z}_{2g}}{\sqrt{\tilde{z}_{2g}^{\,2} + \tilde{y}_{2g}^{\,2}}} \tag{11}$$

hence

$$\frac{S_0 + B_0}{S_1 + B_1} = \frac{2\sin(\rho_{1g} - \rho_{2g})}{2\sin\rho_{2g} - \sin\rho_{1g}}$$

as in Eq. (8) above.

According to the equations of this and the preceding section (Eqs. (6) to (11)) two of eight Ss should feel "head-down". For one of them this was in fact the case, but the other had a distinct inversion illusion. Also in two of the Ss who felt undoubtedly inverted during microgravity, Eq. (6) would yield r at or near zero and Eq. (10) would yield r at or near indeterminacy.

4.4 Finally, the remaining combinations of normalization will be considered, namely that the otolithic and the somatic outputs are separately normalized or that only one of them is.

In the first case the net deviation from d_v=0 on the sled-centrifuge would be virtually identical in all Ss and about midway between the location of the otoliths and the centroid of the mass(es) governing the somatic mechanoreceptors in all Ss. In our 21 control Ss the measured deviation varies between d_v=0 and d_v=-52cm. Hence this hypothesis must be ruled out.

Because it has been shown that the visual SVV is based on normalized otolithic components[4] we shall refrain from treating the case that only the somatic output is normalized, but rather consider the case that only the otolithic output is normalized whereas the somatic one is not.

Hence

$$r = \frac{S_0 + S_1 g \cos\rho}{\sqrt{(U_1 g \sin\rho)^2 + (S_0 + S_1 g \cos\rho)^2}} + B_0 + B_1 g \cos\rho = 0 \qquad (12)$$

The orientation at zero g now depends only on the sign of the saccular bias S_0, if the amount of the truncal bias is lower than unity :

$$r_0 = \frac{S_0}{|S_0|} + B_0 \qquad (13)$$

Predictions of this bias parameter are not longer possible by simple algebraic transformation of equation (12) but can be derived by numerical estimation of the interesting parameters from the data by a computer.

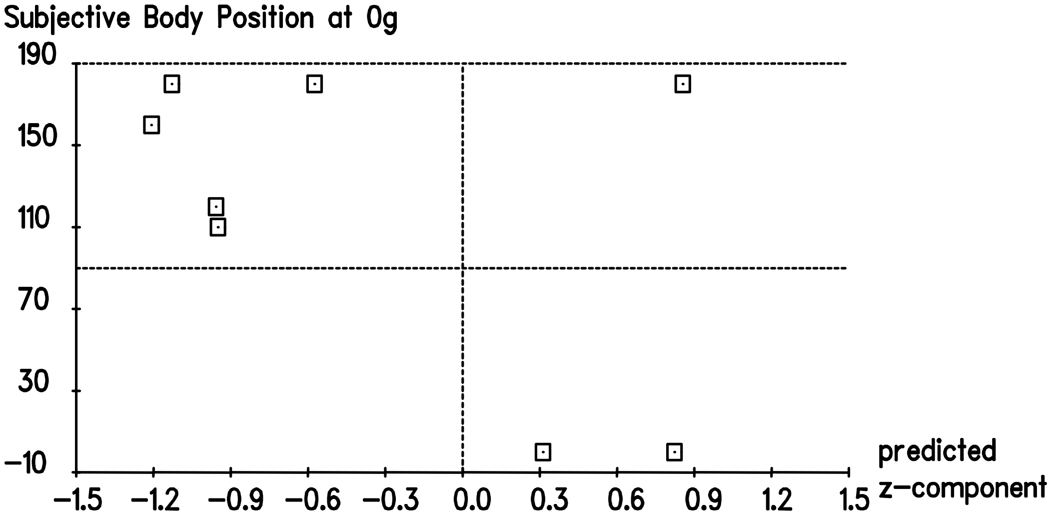

Fig.3 Theoretically predicted Z-component and reported subjective body position in microgravity

Figure 3 shows the predicted amount of the Z-component at zero g which is compared with the reported body position in parabolic flight. All baseline data, namely the SHP at 1g and 2g as well as the SHP on the sled-centrifuge, have been used to evaluate both bias values S_0 and B_0 as well as the amplitude factor B_1 of the truncal gravity system. The other parameters, the saccular and utricular gain factors and the distance between truncal and vestibular system, have been chosen as average best estimates from fits of these parameters according to the static SVV theory[9] to SVV and SHP data of our control groups, and applied identically to all 8 Ss. For two Ss a value on the sled-centrifuge had to be assumed, which, fortunately, turned out not to be critical for the prediction.

Only the prophecy for the S flying in the NASA campaign failed (see upper left part of Figure 3), perhaps because he performed the crucial 1g-2g baseline experiment one year after the flight. But for the other 7 Ss predicted orientation and reported body position at the zero-*g* phase of the parabolic flight correspond indeed.

The amount of the illusion is not correctly predicted by Eqs. (12) and (13). But this is not surprising: A still unpublished dynamical model of the information processing of the SVV (Glasauer, in preparation) is also able to explain the short time constants found for the transition between *g*-levels. As a consequence, the amount of the illusion in the 20 sec of parabolic flight is not given by the static biases but by an independent dynamic parameter.

5. DISCUSSION

Do the results presented support the final hypothesis well enough to yield, by means of the baseline-tests applied here, a reliable prediction of human orientation in space flight? Four caveats should be kept in mind:

5.1 As to reliability, the number of Ss is still small, and some of them were insufficiently trained. Furthermore, for technical reasons, the flat surface of the tiltable board could not be installed within the gondola centrifuge. Hence the results may not be comparable to those of our standard tests[6,7,8].

5.2 As to temporal constraints, the duration of microgravity in a parabola may be too short for a completion of all orientation processes.

5.3 As to the scope of prediction, all models presented pertain to the perception of body position, rather than to the visual SV. The latter (at least its Z-axis component, which is pertinent here,) is notably not influenced by somatosensory information[11]. Hence the saccular bias S_0 alone is expected to determine the visual SV in weightlessness. Therefore, Eqs. (1) to (11) would not necessarily also yield a prediction for the direction of the visual SV at zero *g*; but, remarkably, Eqs. (12) and (13) do so indeed. In this regard, it should be remembered that the "inversion illusion" reported during spacelab 1 and D1 missions[7,8] happened in full view of the visual environment. Hence in future missions it is highly desirable to obtain reports on SVV and body position with, as well as without a visual background.

5.4 As to model completeness, further insight and further specification of the model may emerge from the recent discovery[10] that somatic gravity information appears to originate from two distinctly different sources, viz. the vascular system and the kidneys.

At any rate, the methodology applied here proves to be an effective tool towards understanding human orientation to gravity and may eventually provide a reliable predictive test for its variations in space flight.

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