Physics and Psychophysics of Weightlessness

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THE DEVELOPMENT of aviation is directed toward ever increasing velocities and altitudes. Already, today, aircraft fly at altitudes at which the density of the atmosphere is extremely low. According to the principles of mechanics, reduction or entire lack of weight will ensue during coasting maneuvers at high altitudes because mechanical support by the atmosphere is lacking.[5] Consequently, the pilots of rocket aircrafts will have to familiarize themselves with the occurrence of sub-gravity and zero-gravity states.

In these states, little or no forces are exerted on the airman, causing him to experience little or no sensations of weight. Whereas the physiological and psychological effects of gravity greater than 1 g have been widely studied, and the tolerance limits for men under various conditions of positive and negative acceleration have been determined, little is known as to human behavior under conditions of reduced gravity. With the development of high-altitude, high-velocity flying, however, physiological and psychological functions in the sub-gravity and zero-gravity states will become a major subject for research. This paper attempts to delineate some of the physical and psychophysical problems associated with the lack of gravity.

PHYSICS

Within the gravitational field of the earth a body derives its weight from the mechanical support that prevents it from falling freely. The forces experienced by the body expressing themselves as weight become evident only if the body is supported. If a body moves vertically downward with an acceleration of 1 g, i.e., after having lost its support and falling freely[1,5] with a constant acceleration, an upward pulling force of inertia becomes effective, which exactly eliminates the body's weight. In this case, the body will find itself in the *zero-gravity* state. If a downward directed, constant acceleration smaller than 1 g is applied, the upward pulling force of inertia will not entirely abolish the body's weight. In this case the body is in a state of *sub-gravity* of a certain amount.

In applying these principles to the human body, another mechanical factor, elasticity, must be taken into account. Hence, the behavior of an elastic body (a rubber ball for instance) under conditions of normal gravity and zero-gravity will be discussed.

As already mentioned, this rubber ball has weight only when it is supported. As a consequence of the forces associated with this support, a certain field of elastic forces is generated on the surface and in the interior of the body. Consequent to the process of placing the body onto its support, an elastic deformation takes place. This deformation is characterized by a state of equilibrium between the elastic forces within the body and the gravitational forces.

The gravitational forces which act on each individual molecule of the body are eliminated by the forces of inertia as soon as the body moves along a Keplerian trajectory with respect to the center of attraction. In the latter condition, the body finds itself in the gravity-free state. The transposition into this state brings forth a change in the above-described field of the elastic forces in the interior and on the surface of the body. This field of forces attains a new state of equilibrium which depends solely on the structural elements of the body, such as elasticity, shape, and material constitution, and which is characterized by the condition that the sum of all elastic forces acting on each point of the interior and the surface of the body vanishes. These conditions hold as long as the body is at rest or moves at a constant velocity relative to the gravity-free system. In all cases of accelerated motion, however, forces of inertia become effective and play the role of a quasi-gravity. The conditions involved in these phenomena can most easily be demonstrated by means of a hypothetical experiment.

It is assumed that the elastic body is suspended in a system of springs and subjected to a plain sinusoidal motion under conditions of zero-gravity. The mechanical characteristics of the springs, the proper frequency of the system, the conditions of excitation, and the amplitude may be such that the acceleration peaks amount to ± 1 g. Frictional forces are neglected. As is known, the kinematic and dynamic conditions can be described by the equations

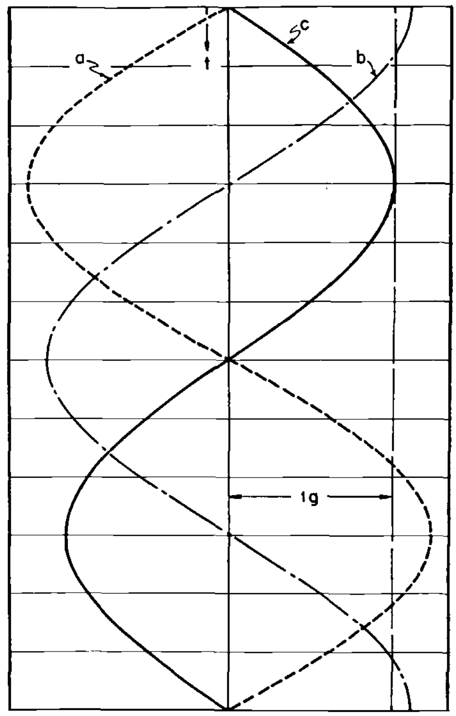

Fig. 1.

$$s = a \cdot \sin(\omega t - \Phi) \quad (1)$$

$$\frac{ds}{dt} = v = a \cdot \omega \cos(\omega t - \Phi) \quad (2)$$

$$\frac{d^2s}{dt^2} = b = -a \cdot \omega^2 \sin(\omega t - \Phi) \quad (3)$$

in which s = the distance of the body from the zero point, a = amplitude, ω = frequency, v = velocity, b = acceleration, Φ = phase constant, and t = time. The three functions are demonstrated graphically in Figure 1 (a, b and c). As can be read from Figure 1 (c) and from equation 3, the body is subject to forces varying in a sinusoidal way. These forces provide the body with its full weight at the peaks of acceleration. At the zero points the body finds itself in the gravity-free state for an infinitesimal period of time. It may further be pointed out that the body experiences a periodic change in the direction of the quasi-gravity. It follows from these conditions that the elastic body is subject to periodic elastic deformations, since the forces at play are invariably pulling outward, away from the zero line.*

The aforementioned consideration concerning the behavior of an elastic body under conditions of 1 g and zero-gravity will be taken as a basis for an analysis of the psychophysical phenomena associated with the gravity-free state.

PSYCHOPHYSICS

In theorizing on the psychophysical phenomena related to the gravity-free state, one has to consider that the human body is also an elastic body. One must be aware, also, that the human body, with its system of mechanoreceptors, possesses an instrument that provides information as to the forces acting on or within the body. Among the mechanoreceptors one discerns the following ones: (1) vestibular apparatus consisting of the semicircular canals, utriculus and sacculus as receptor organs for rotary and translatory motion; (2) the basket-like nervous plexuses around the hair follicles and the Meissner corpuscles as the receptor organs of the pressure sense of the skin; (3) the muscle spindles as the receptors of the myotatic reflexes and of the muscle sense, and (4) the Vater-Pacini corpuscles as receptors of the posture sense.**

*Under conditions of 1 g such changes in direction of "weight" can only be realized if the body is moved downward at an acceleration greater than 1 g. Such conditions, however, can hardly be realized for any length of time, so that these changes in direction of "weight" could not manifest themselves psychophysiologically.

In the following the function of the semicircular canals is not considered since the discussion is centered chiefly around the effects of translatory accelerations. The behavior of an elastic body under the various conditions previously described is now applied to the human body.

There are five different cases to be considered:

1. Under normal conditions (g = 1), at rest or at a constant velocity.
2. Under normal conditions in accelerated motion.
3. Within a gravity-free system at rest or at a constant velocity.
4. Within a gravity-free system with involuntary accelerated motion of the body.
5. Within a gravity-free system with voluntary accelerated motion.

The above five cases will be discussed in detail as follows:

1. *Under Normal Conditions (g = 1), at Rest or at a Constant Velocity.*—Since we find ourselves almost invariably in a fully supported state (standing, sitting, lying on a support), the state characterized by 1 g must be considered the normal mechanopsychophysical state of the body. This condition is taken by the individual as the static zero state in which no sensations of force and acceleration

**For a detailed compilation concerning the mechanoreceptors of the skin and muscles, see H. Strughold.[6]

are normally experienced. In terms of physics or more specifically of mechanics, the body is then in a certain state of mechanical tension. As is the case with any elastic body, within the human body there is a field of elastic forces which carries the weight of the body and its parts. Depending on the spatial position of the head in the position of rest, the end organs of the sacculus and urticulus are stimulated in a certain manner. This is brought forth by the weight of the otoliths and the membrane of the otoliths which elastically deform the epithelial hairs by pressure, pull, or shearing. Furthermore, the weight of the body and its parts rests upon the supports; this leads to a stimulation of the end organs of the pressure sense at the contact areas of the skin. This stimulation is equally produced by the elastic deformation of the respective parts of the body. The specific stimulus for the sensory nerves of the pressure sense is not pressure as such, but change in pressure. This is the reason why an extremely fast adaptation to the prevailing state of tension on the surface of the body is observed.

The receptors of the muscle sense experience a stimulation which also stems from the general field of elastic forces found within the body.

In this connection it may be pointed out that, among the four sense modalities mentioned, only the pressure sense is distinguished by a pronounced objectivation. In contrast to this, the function of the sacculus and utriculus as well as the muscle sense and the posture sense are more closely linked to the reflex mechanism of the body. Nevertheless, muscle sense and posture sense can be somatized to such an extent that the sensations provided by these senses can become conscious.

2. *Under Normal Conditions in Accelerated Motion.*—The inner field of elastic forces, which prevails within the body at rest under 1 g, is changed in a certain manner by any voluntary and involuntary accelerated motion. These changes effect a pattern of stimulation of the mechanoreceptors that, as a whole, is accompanied by sensations of moving and/or being moved.†

3. *Within a Gravity-free System at Rest or at a Constant Velocity.*—The weight of the body and its parts vanishes under conditions of zero-gravity. At the same time that component of force which causes the gravitational deformation of the body vanishes also. Similar to the above-mentioned elastic body, the human body, in the gravity-free state, will build up an inner and outer field of forces, in which the sum of all elastic forces acting on all points of the body vanishes. In transposing the human body into this new state of equilibrium the stimulation of the mechanoreceptors is altered decisively. The otoliths and membrane of the otoliths, deprived of their weight, do not exert any pull or pressure on the end organs of their respective sense apparati. The stimulation of the receptors of the pressure sense generally vanishes, since the body does not require any support (i.e., there is generally no

†It must be considered that these additional forces can only be small relative to gravity, which is constant as to direction and size. Forces surpassing gravity to a great degree exist for only extremely limited periods of time as in shocks.

contact with any foreign body). In the gravity-free state the body and its parts can do without any outer elastic force to carry the weight. The tonus of the muscles in a general rest position under these conditions depends solely on those forces which stem from the field of elastic forces based on the natural cohesion of the body's parts. The receptors of the muscle sense will be placed under a stimulation that cannot be realized under conditions of 1 g.

The receptors of the posture sense experience hardly any noticeable change. These receptors are localized chiefly in the connective tissue of the muscles and the tendons that have little elasticity. Elastic deformations of this tissue are caused far more by posture and movements of the limbs than by changes in weight.

A stimulation of the mechanoreceptors, as a whole, can be experienced only in the situation of falling freely.

The sensations associated with the free fall are chiefly characterized by the impression that all support is giving way from under one. In fact, the sensation of falling can almost be identified with this kind of experience. It may further be pointed out that the above-described stimulation of the system of mechanoreceptors is accompanied by a number of motor reflexes such as statokinetic reflexes of the limbs, innervation of the muscles of the neck, reflexus vestibulo palpaebralis, etc. These reflexes are typical for sudden-fall reactions and other abnormal reactions of the mechanoreceptor system.

Nothing is known, by nature, of the adaptability of the individual to the situation of falling freely. The possibility or even probability of such an adaptation, however, may be presupposed as a working hypothesis for the following discussions. This hypothesis is identical with the statement that the above-described field of elastic forces of the body at $g = 0$ is taken by the individual as a new psychophysical zero-state.

4. *Within a Gravity-free System with Voluntary Accelerated Motion.*— In analyzing the conditions associated with the involuntary accelerated movement at $g = 0$, the human body may be subjected to the beforementioned experiment. Considering the possible adaptation to the gravity-free state one must distinguish two different cases: (1) the individual being adapted to the condition $g = 1$; (2) the individual being adapted to the condition $g = 0$.[7]

In the first case it is assumed that the test subject is an individual unadapted to the gravity-free state. The state of adaptation to the conditions of $g = 1$ is supposed to last for the duration of the hypothetical experiment. It is further assumed that all other sensory stimulations—especially of the eye—are excluded. The longitudinal axis of the subject's body is oriented parallel to the oscillatory movement. The forces acting on the body under these conditions can be read from Figure 1(c); i.e., the mechanoreceptors will be placed under a stimulation that varies periodically as to size and direction. It can easily be seen that the peaks of acceleration occur at the turning points of the motion, reaching the amount of $\pm$ 1 g according to the example. It is at this place that one must recall that man possesses an orientational scheme related to position and motion. This scheme is, to a large extent, based on the action of gravity. According to this scheme the direction "down" is identical with the direction of gravity. In the hypothetical experiment we are dealing with accelerated motion and consequently with the occurrence of quasi-gravity stemming from the forces of inertia. As mentioned before, this quasi-gravity is invariably pulling outward, away from the zero line, while it vanishes in the zero position. As has been the case with the elastic body previously described, the subject's body will undergo elastic deformations, which are accompanied by a corresponding stimulation of the mechanoreceptors.

A full period of the motion is subdivided into four phases which are designated by I, II, III, and IV in the graph of Figure 2. This graph gives the locus of the subject as a function of time. At the point A the subject finds himself in the gravity-free state for an infinitesimal period of time. Consequently, in the beginning of phase I one has to anticipate a fall sensation. The "fall" of the subject will subsequently be "braked" in approaching the point B.‡ Since, at the point B, the acceleration attains the value of 1 g the subject may possibly have the sensation of having been "braked" to a standstill. In this instant the subject can interpret this situation as being suspended and fully supported by the straps in the normal position

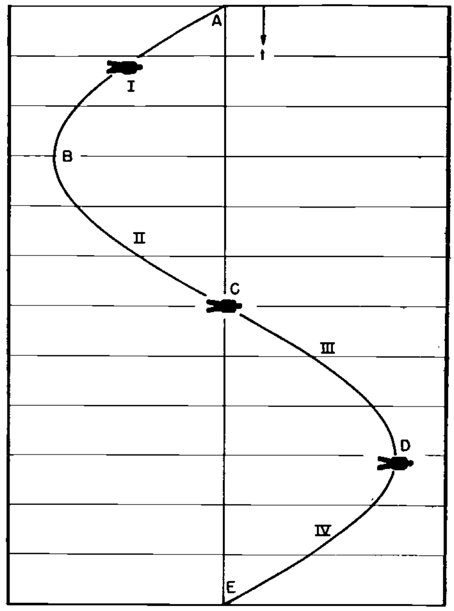

Fig. 2.

(feet downward).

During the phase II the conditions of phase I are reversed. In the beginning of phase II the pressure of the straps begins to decrease. Consequently one has to expect a sensation associated with a transition from a fully supported state into the state of falling freely. The latter is reached at the point C where, with g = 0, any fashion of support vanishes. During the phases III and IV the same phenomena are repeated, with the difference that during these phases the subjective direction "down" is localized in the direction of the head. From this it can be concluded that, during one full period, the subject experiences a conversion of his bodily position relative to his subjective "down" direction. Under normal conditions of 1 g, such a phenomenon cannot be experienced unless the subject is turned around.

‡Quotation marks indicate the sensations experienced by the subject.

It must be pointed out that the phases III and IV (head down) will be accompanied by more pronounced sensations since the end organs of the sacculus and utriculus show much stronger reactions to pull than to pressure. One can therefore expect that this kind of motion will be experienced as highly asymmetrical.

In dealing with the second case (a subject adapted to the conditions of zero-gravity) it can be expected that the sensation of falling freely at the points A, C, and E has vanished. An individual adapted to this state will experience a sensation of rest in the gravity-free state. In this it must be considered that, at g = 0, every additional force acting on the body and on the mechanoreceptors will be experienced as a force and will be accompanied by a feeling of being moved. This contrasts to the conditions of g = 1, when a continuously acting force (namely, gravity) is associated with the sensation of being at rest. Consequently it can be assumed that an individual adapted to g = 0 will experience a lift sensation when transposed into the natural state of g = 1. This sensation will prevail until the subject is readapted to the normal state. Returning to the hypothetical experiment one must assume that the subject has a sensation of rest at the point A. In approaching the point B the pressure of the straps increases, the end organs of the vestibular apparatus are stimulated by pressure so that the subject will experience an increasing sensation of lift, head "up." This sensation of lift reaches a maximum at the point B, decreases during phase II and vanishes at the point C. During the phases III and IV these sensations are repeated, yet, with the difference that the subject experiences a corresponding sensation of lift, feet "up."

5. *Within a Gravity-free System with Voluntary Accelerated Motion.*— The body and the limbs cannot be moved voluntarily without being accelerated. As long as these accelerations last, one will observe an elastic deformation of the body and its parts and, consequently, the stimulation of the mechanoreceptors will be altered.

Movements of the whole body as they occur if one moves voluntarily will be discussed first. The conclusions arrived at in the discussions of the before-mentioned hypothetical experiment can immediately be applied; only the case of an individual adapted to g = 0 may be considered.

An individual may be at rest at the point A and may subsequently change his place to come at rest again at the point B. The subject can accomplish this by either pushing himself away from the point A or by pulling himself in the direction of the point B, using a handle or a similar device. While being accelerated away from the point A, the subject finds himself in a situation similar to that prevailing in the phases I and II of the experiment mentioned last. Consequently, the subject experiences sensations of lift (head "up") during the acceleration period. The subject finds himself again in a gravity-free state while floating from the point A towards the point B. At the point B the subject brakes the motion by stemming off the wall or another object, with his hands. The deceleration arising in this process stimulates the mechanoreceptors in such a manner as observed during phases III and IV of the experiment mentioned above. During the period of deceleration the test subject experiences the sensation of lift (feet "up"). From an analysis of this process the following remarkable phenomena associated with voluntary alterations of one's place can be derived: During the state of rest at the point A, no directions distinguished as "up" and "down" exist. The six boundary surfaces of the ambient room are all "walls"; floor and ceiling are defined solely by convention. During the phase of acceleration the wall bearing the point A becomes "floor." During the phase of floating, i.e., while the subject moves at a constant rate of velocity between the points A and B, the same state as experienced at rest prevails. During the phase of deceleration the wall bearing the point B becomes "floor," against which the subject stems with a "handstand." Similar to the hypothetical experiment, voluntary alterations of one's place involve a subjective tilting "up-down" by 180°. It must be added that the end organs of the semicircular canals are also stimulated in almost all cases of voluntary and involuntary movements. These stimulations vary strongly, depending on the posture of the head relative to the direction of acceleration and deceleration. The occurrence of illusions of being rotated and a corresponding activation of the reflexes coupled with the stimulation of the semicircular canals cannot be excluded.

In moving the limbs voluntarily under conditions of zero-gravity one will observe a disturbance of the co-ordination of the relative stimulations of the end organs of the muscle sense and the posture sense. Lifting the arm at $g = 1$, for instance, requires not only overcoming of the arm's inertia but also of the arm's weight. In each position of the arm, a certain stimulation of the posture sense is co-ordinated with a certain stimulation of the muscle sense. Under conditions of zero-gravity this co-ordination is disturbed, since the arm has no weight and only the arm's inertia must be overcome in moving it. This means that the stimulation of the muscle sense must change while the stimulation of the posture sense is virtually equal to that prevailing under conditions of 1 g. This phenomenon will produce a dissociation of the normally concerting sensations of the muscle sense and the posture sense.

The entire range of phenomena discussed so far is related to the stimulation of the mechanoreceptors alone. Other perceptual cues, especially visual ones, are excluded. It must be expected that including the eye into the stimulus-sensation mechanism will decisively alter the picture. It can be assumed that use of the eyes will be of considerable help in overcoming the sensation of falling freely subsequent to a transposition into the gravity-free state. For, a visible movement of the body relative to its surroundings does not exist, contrary to the fall situation on earth.

The sensations of the individual associated with the swing experiment described above may also be modified decisively if the subject is not blindfolded. It can be assumed that the in-

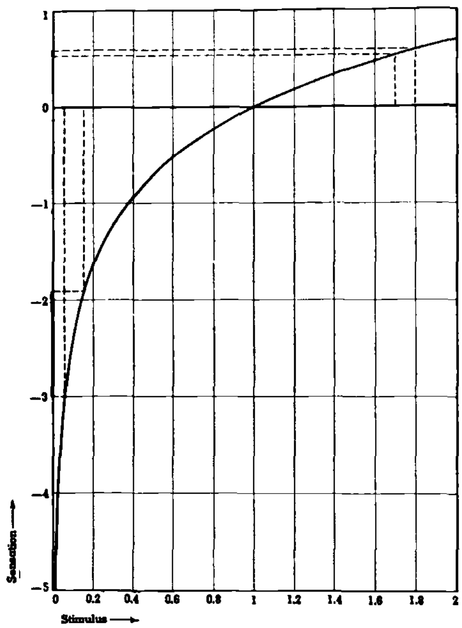

Fig. 3.

dividual will be able to identify correctly the oscillatory movements by a visual evaluation of his kinematic situation. In this, training, experience, and intelligence will play a part. As is known, for instance, a beginner perceives the horizon as tilted during sharp turns of an aircraft, while an experienced flyer is able to maintain the ground as a horizontal reference plane even during complicated flying maneuvers. Virtually at all times, the experienced flyer can identify objectively his position and motion relative to the ground. By the use of his eyes man can learn to suppress the false information given by the mechanoreceptors. Campbell[2] (1950) has specifically pointed out the importance of this phenomenon in relation to the problem of orientation in the gravity-free state.

While considerable help in the situation of zero-gravity can be expected when visual cues are included, another phenomenon pertaining to the functions of sense organs must be considered as an aggravation. This aggravation is based on the Weber-Fechner Law (Gauer).[3]

The Weber-Fechner Law, as is known, describes the relation between the intensity of a stimulus and the intensity of the co-ordinated sensation. Mathematically speaking, this law maintains that the intensity of the sensation is proportional to the logarithm of the corresponding stimulus. We are led to assume that this law holds also for the function of the sense of gravity, though the sense of gravity is a complex structure composed of the function of the vestibular apparatus, of the pressure sense of the skin and of the proprioceptors of the muscles. As mentioned before, the assumed validity of the Weber-Fechner Law for the gravity-sense leads to earnest consequences in view of the gravity-free state. In regard to this see Figure 3. This figure demonstrates the simple logarithmic curve, $y = \log \text{nat}\, x$, whence x represents the stimulus and y the corresponding sensation. The logarithmic curve intersects the x-axis at the value $x = 1$ and approximates the value $y = \infty$ for $x = \infty$; for $x = 0$ the value of the logarithm becomes $y = -\infty$. The relation between stimulus and sensation is fairly well represented by the central part of the logarithmic curve, as far as the well-investigated senses are concerned. The values $x = 0$ and $x = \infty$, however, are not realized biologically; there, caused by the absolute threshold and the pain threshold, respectively, natural limits of the function of the sense organs are imposed, resulting in certain deviations from the ideal logarithmic relation. The value $y = 0$ for the sensation does not indicate that no sensation prevails for the stimulus $x = 1$; the value $y = 0$ must be defined as a sensation corresponding to a mean intensity such as will be found for the eye at normal room illumination (50 to 100 foot-candles), for the ear at a mean noise level (40 to 50 db). In our case, the sensation of gravity which corresponds to the value $y = 0$ may be set equal to the sensation which is registered at a gravity of 1 g.

The curve which represents the Weber-Fechner Law exhibits an important factor. A range of sensations covering the section from zero to infinity corresponds to the range of stimuli from $g = 1$ to $g = \infty$; a range of sensations covering the section from zero to minus infinity corresponds to the range of stimuli from $g = 1$ to $g = 0$; consequently, if we reduce gravity from $g = 1$ to $g = 0$, we cover a range of sensations which is as large as the range of sensations corresponding to an infinite increase of acceleration starting from $g = 1$. The function of the gravity sense becomes particularly critical in the proximity of $g = 0$. As can be read from the curve, strong sensations are caused by minute changes of acceleration, if man is subjected to states of gravity close to zero. Yet, accelerations of critical amounts are already produced by voluntary and non-voluntary body movements accompanied by correspondingly strong sensations of acceleration at $g = 0$. At $g = 1$, such small additional accelerations are below the threshold according to the Weber-Fechner Law. At this time there is no way of knowing how the co-ordination of the optical sense and the mechanoreceptors at the peak of their sensitivity will work.

The analysis of the presumable psychophysical phenomena in the gravity-free state had, by necessity, to depend on assumptions and conclusions by analogy. Here, only the experiment will decide. It is intended to outline in a second paper[4] the specific psychological problems associated with the zerogravity state.[5]

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