A New Solution to the Problem of the Subjective Vertical

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Based on new evidence and the extensive literature, this report develops an outline of a comprehensive theory of the subjective vertical (SV) in humans. Traditionally the large deviations of the SV from veridicality are attributed to a failure on the part of the *gravity* systems to correctly perform the necessary coordinate transformation on the visual system. It is experimentally demonstrated, however, that in the control of posture the gravity systems do in fact work close to perfection in positions where the deviations of the SV from the physical vertical are almost largest. Since also the visual system is known to process angular information veridically in the respective range, the intervention of a third agent is suggested, namely a tendency to shift the SV towards the person's own longitudinal axis ("idiotropic vector"). The predictions of the theory are confirmed experimentally, proving that not only the visual but also the haptic zenith is shifted towards the long axis by strongly correlated amounts, when the head is pitched backwards. The theory is also shown to be compatible with, or amenable to typical properties of the SV response characteristic [1], quantitative neurological data on primate gravity receptors [2], a theory of postural control worked out earlier [3], and a particular type of non-linear interaction also found in other orientation systems [4].

In human subjective experience, verticality of objects seen is a phenomenon of consummate clarity and unquestionable self-evidence [5]: Even very slight slants are easily detected. For many reasons, verticality of the visual world is important for a living being who carries mobile eyes in a mobile head above a body balanced in a labile equilibrium on a mobile base. Yet to ensure this presents a problem: Certainly, cues for verticality might often be inferred from an analysis of the features of the visual image alone, as has indeed been demonstrated [6]. Yet, if, as in the experiments to be reported here, such features are absent, verticality must be secured otherwise, for instance (as in analogous technical systems) by keeping the input platform, that is, the eyeballs always level: Whether an object is vertical could then be told from the position of its image on the retina. In humans, however, compensatory eye movements are either totally insufficient, as in roll, or superseded by roving voluntary diversions of gaze as in pitch. Consequently, the position of the eyes must be accounted for whenever the direction of an object relative to the head shall be assessed. Extensive evidence shows in fact, that the visual system, conjointly with the system which monitors eye position, is able to provide, by what mechanism ever [7], information about the angular relations of the visual world *with reference to the head*. In order to assess its relation *to the vertical* then, for instance the inclination of a straight line presented in a fronto-parallel plane when the head is tilted in the same plane, the information about the angle between line and head must be somehow compared within the central nervous system with information about the angle between the head and the vertical. Fig. 1 shows what actually happens if a test person (S) is asked to rotate, by remote control, a luminous line in otherwise complete darkness until it appears vertical: Except for roll angles (ρ) near the upright and upside down positions most Ss set the line to very large deviations ($\delta=\rho-\beta$) from the physical vertical (from the dashed line in Fig. 1, which is at $\beta=\rho$). The phenomenon has been

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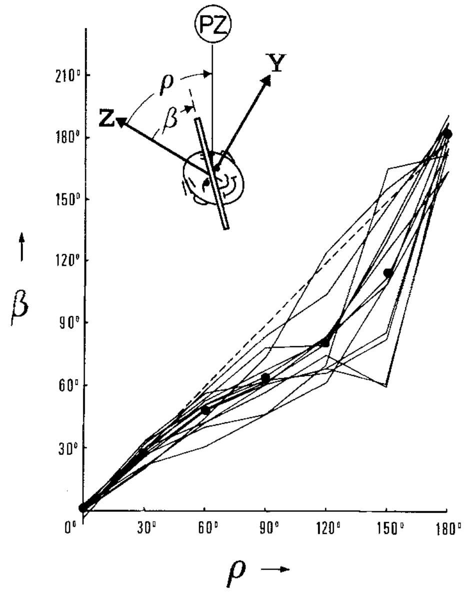

Fig. 1. Dependence of the subjective vertical on the roll position (head and body) in 12 Ss, as found by Udo de Haes [18]. Abscissa: angular deviation ρ of the head's Z-axis from the physical vertical (X-axis rostrad, Y- and Z-axes as shown). Ordinate: angular deviation β of (the upper end of) a luminous line from the Ss' Z-axis, dots at the means [1]

discovered by H. Aubert in 1861 [8], and since been extensively investigated. A sufficient explanation of the phenomenon, however, has not yet been given (cf. [6, 9–11], and the assessment by I.P. Howard in his recent comprehensive review [12]).

What could be the cause of the considerable deviations from veridicality which are found in nearly all persons? The suspicion that the phenomenon might be a darkroom artifact had to be dismissed after Helmholtz's finding that it persists in full daylight, e.g. if a black line is set to the vertical in front of a homogeneously white wall. We then seem to be left with the alternative that *either the visual and eye position systems are unable to procure a correct representation of the position of the line relative to the head or else the gravity systems are unable to procure a correct representation of the position of the head relative to the physical vertical.*

In order to test the first possibility, one may ask the Ss to judge the roll inclination of a line *relative to their heads*, irrespective of the line's verticality and the head's position. Depending on the methods used [13–15], one finds small deviations from a correct judgement of the angular relation (β) between line and head only at certain oblique line positions. Yet constant errors of 20 or 30 degrees, like those regularly recorded in the paradigm of Fig. 1, have never been reported.

Because the visu-ocular system is evidently able to yield nearly veridical angular information, we seem to be forced to conclude that the deviations of the subjective vertical are caused by a deficiency of the gravity systems. As to the result of Fig. 1, this would imply that, except for small angles of head roll in some persons ("Müller phenomenon"), the gravity information leads to an *under*estimation of the angle of roll. If a person at a roll position of 90° to the right, for instance, sets the line at $\beta=60°$, that is 30° to the right of the physical vertical, the head roll must have been underestimated by that amount. By the same token, the gravity systems would indicate a 90° roll position, if the head is objectively tilted much more, in fact to that position where the line is set at a right angle to the head's median plane ($\beta=90°$), that is (compare Fig. 1), when the head of most persons is objectively in a roll position of 120° or more! This conclusion is all the more cogent because, in the experiments just mentioned, judgements of the relation between head and line are veridical at $\beta=90°$. All one has to do then for a critical test of the hypothesis is to ask a person to actively assume a 90° roll position in total darkness, and then, in that actively chosen position, to set a line to the vertical. The experiment is done by means of the apparatus shown in Fig. 2. Lying on their side

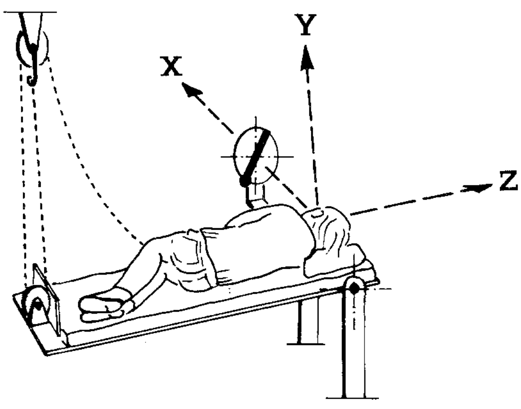

Fig. 2. Set-up for controlling one's roll position. The S, her head fixed by means of a bite board, lies on a padded board which may be rotated about the S's X-axis by remote control of a windlass. First, in total darkness, the S is asked, starting from alternating head-up or head-down positions, to rotate herself until she feels horizontal. Secondly, in that position, she is asked to set the line in front of her to the vertical. The results are shown in Figs. 3 and 4

on a board which they could rotate by remote control about a horizontal axis situated directly below their heads, the Ss were asked, starting alternatingly from arbitrarily chosen head upward or downward positions, to rotate the board until they felt perfectly horizontal. In that position they were asked to open their eyes and rotate to the vertical, also by remote control, a luminous line, which was displayed 60 or 90 cm in front of them in alternating roll deviations of random amounts. As demonstrated in Figs. 3 and 4, neither of the above expectations have been borne out. Rather than winding up with considerably larger roll deviations than 90°, almost all persons were excellently (S.D. around 0.9° or 1.4°) able to roll themselves very closely into the intended 90° position. The subjectively vertical line positions, however, did not at all cluster around $\beta = 90°$. Rather they showed typical personal deviations corresponding to those which had been found in the paradigm of Fig. 1, averaging around $\rho - \beta = 21°$.

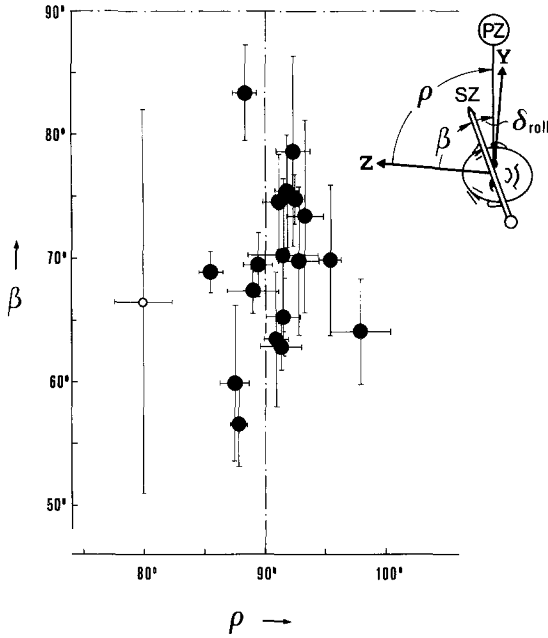

Fig. 3. Result of the test sequence of Fig. 2 in 19 students. Abscissa: roll angle ρ (see inset) at self-adopted horizontal position; ordinate: subjectively vertical line settings (angle β, see inset) at that roll position; brackets: standard deviations

The inescapable consequence is then that the visu-ocular as well as the gravity systems, at least in the positions tested, do in fact yield a reasonably veridical measure of the relevant angular inputs, and hence neither can be the source of the large deviations actually displayed. Are we to conclude, then, that the human brain, certainly the most sophisticated neural structure known, should be unable to properly connect those two inputs, although it is well able to properly connect them to their adequate perceptual and motor outputs separately? I rather contend that the two inputs are in fact well connected, in a way that would in our case be perfectly sufficient to provide for a reasonably veridical visual vertical, were it

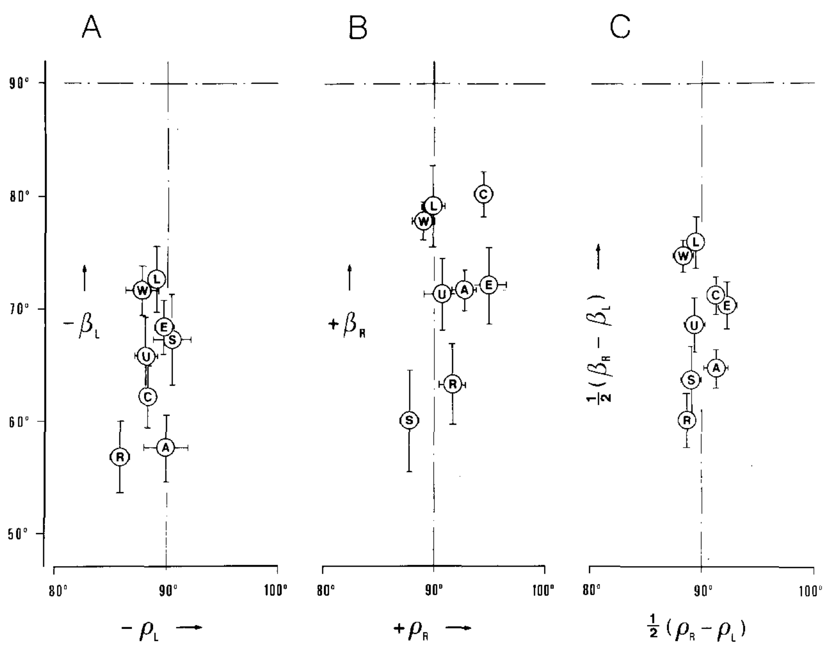

Fig. 4. Result of the test sequence of Fig. 2 in 8 well practised Ss (staff members). A) Roll to the left (ordinate and abscissa negative!), B) to the right, C) mean differences. All symbols as in Fig. 3

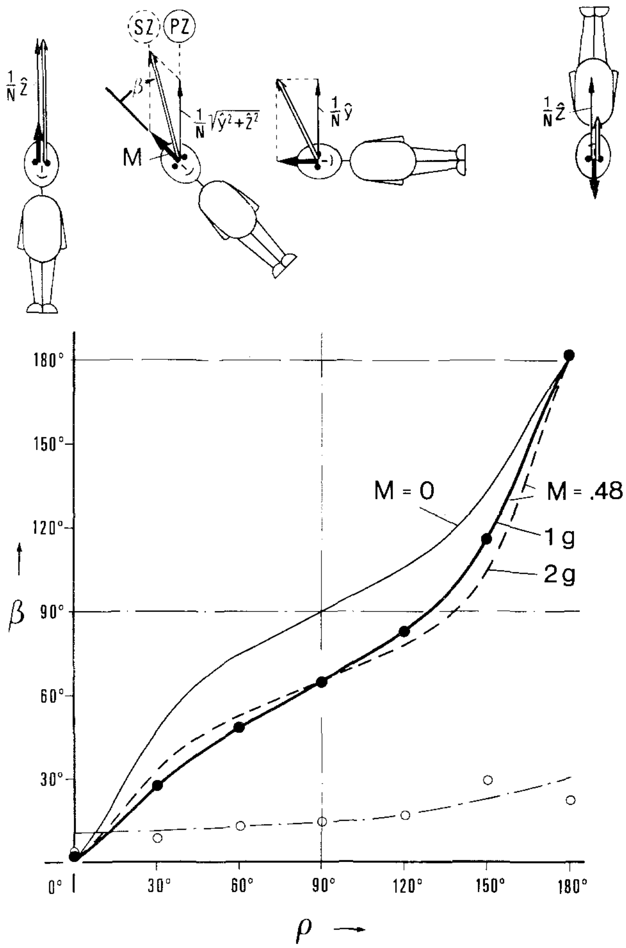

Fig. 5. Above: idealized pictograph of subjective vertical as resultant (double-line arrow) of a gravity vector (single-thin-line arrow) and an idiotropic vector (fat-line arrow) in the roll positions ρ of the abscissa. The physical zenith (PZ) is up, the subjective zenith (SZ) in the direction of the resultant vector. Below: fat line: adaptation of the theory to the means (dots) of Fig. 1. Dashed line: prediction for contrifugation to $2g$. Thin line ($M=0$) shows what would happen if the idiotropic vector were absent. Open circles: three times empirical standard errors (from [18] and [1]). Thin dashed line: reciprocal of the resultant vector of the adaptation. It is done with just 3 free parameters, under the assumption of veridical self-adopted 90° roll, pitch, and yaw positions, a 30° rearward tilt of the labyrinth's Z-axis relative to the head's, and

$$\hat{x} = \cos 30°\, \tilde{x}_{\mathrm{UTRIC}} - \sin 30°\, \tilde{z}_{\mathrm{SACC}};$$
$$\hat{z} = \cos 30°\, \tilde{z}_{\mathrm{SACC}} + \sin 30°\, \tilde{x}_{\mathrm{UTRIC}}$$

where a tilde denotes labyrinth-fixed coordinates. Furthermore (cf. Eqs. 1a, 2a) with $n=1$, $\tilde{F}_{y_1}$ set to unity, $\tilde{F}_{x_1}=0.7$ and $\tilde{F}_{z_1}=0.54$, the nonlinearity of the utricular components being accounted for (crudely) by power functions with exponents $u=1+0.3=1.3$ and that of the saccular component (necessarily) with an exponent $s=1-0.3=0.7$; the amount of the idiotropic vector M (again necessarily) $=0.48$. Note that $\tilde{F}_{z_1}/0.5\,(\tilde{F}_{x_1}+\tilde{F}_{y_1})=0.64$.

not for the intervention of a third party: The theory to be presently developed maintains that the direction of a person's "subjective zenith" (SZ) results from an interaction of two tendencies – a tendency governed by the gravity systems to localize it in or close to the direction of the physical zenith, and a tendency, of unknown, probably central nervous origin, *to localize it in or close to the direction of the person's own longitudinal (Z-) axis*. The latter shall be named "idiotropic tendency".

Furthermore, the theory explains the striking difference in veridicality of the line settings and those of the self-adopted positions by assuming that the subjective vertical and the body position relative to gravity are computed and monitored in different ways. Nevertheless, both may be based on the same gravity inputs. Provisionally, until there is evidence to the contrary, exactly this shall be assumed in the following formulations. In any case, however, *the idiotropic tendency*, as shown under the conditions of our experiments, *is claimed not to partake in postural control at all.*

The core of the theory is most readily understood, if the hypothetical agents causing the two tendencies are represented graphically as vectors. Although a gross simplification, this representation, as well as the mathematical structure describing it, are nevertheless rather useful as a first approximation. As shown in Fig. 5, the cause of the gravity tendency is represented as a unit vector pointing at the physical zenith, whereas the idiotropic vector points in the direction of the person's long axis. Its amount (0.4 on average) is supposed to be a personal constant. The resultant vector points at the subjective zenith, its length indicating the person's certainty about its location. The theory predicts, therefore, that the variance of the settings of the luminous line, in fact, their deflection by any intervention should be inversely proportional to the length of the resultant, that is, increase with the angle of roll (cf. Fig. 5). And this has indeed been found in all known experiments of this kind [1, 16–19, 29, 30]. Thus, the theory yields a straightforward explanation for the implausible "decreased effectiveness" of the gravity system with increased angle of tilt.

The Gravity Vector

That the cause of the gravity tendency may be represented as a vector is a consequence of the fact that the labyrinthine gravity receptors in the utricle and the saccule are sensitive to linear (translatory) acceleration, and arranged in such a way that three nearly orthogonal scalar components may be computed from their outputs [3, 4]. Again simplifying the real situation, let us assume that the utricle is positioned as in Fig. 6 and the saccule as in Fig. 7 (whereas their X- and Z-axes are in fact tilted backwards relative to the X- and Z-axes of the head). If the impulse rates of the utricular units are summed up like those of the two in Fig. 6, and the saccular impulse rates like those of Fig. 7 (as worked out in detail in [3] and [4]), we get, at equilibrium and in the case of pure roll, a utricular component $\hat{y}$, which may be approximated as follows:

$$\hat{y} = F_{y_0} + F_{y_1} g \sin \rho + F_{y_2} g^2 \sin^2 \rho \tag{1}$$

and a saccular component

$$\hat{z} = F_{z_0} + F_{z_1} g \cos \rho + F_{z_2} g^2 \cos^2 \rho \tag{2}$$

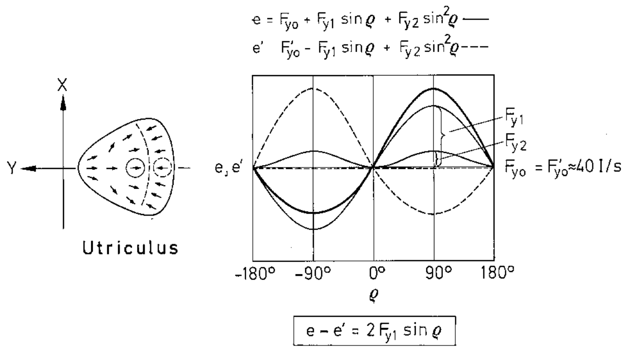

Fig. 6. Formation of the utricular y component by summation according to [3] and [4]. The principle is shown paradigmatically for two afferent units. The arrows point into their polarization direction, i.e. the direction which a force vector must have to yield maximal excitation. The *sign* of summation of their discharge rates e (in impuls per second, I/s) is determined according to their polarization directions relative to the Y-axis; $g=1$. The amplitudes resulting from the summation are denoted by the F-parameters of Eq. (1)

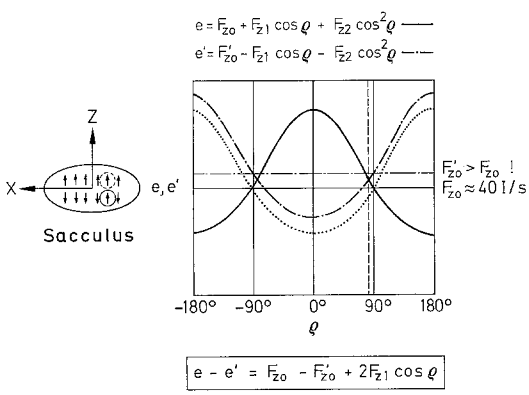

Fig. 7. Formation of the saccular $\hat{z}$ component by summation of the discharge rates e according to polarization directions relative to Z-axis [3, 4]; otherwise as in Fig. 6

where g is the acting linear acceleration, divided by $9.81\,\mathrm{m \cdot s^{-2}}$, F_1 the amplitude of the terms which are linearly dependent on the acting shear force, F_2 that of the quadratically dependent ones, and F_0 the terms which are shear-independent. Whereas F_{y_1} and F_{z_1} should be (also) dependent on the number of receptors of the utricle and the saccule, respectively, the four other parameters should be zero or very small indeed, because the assumed type of summation would lead to cancellation of the respective receptor biasses and quadratic nonlinearities. This is strictly true for the $\hat{y}$ component, if the receptor patterns of the utricles are bilaterally symmetrical. There are reasons for supposing, however, that the resting discharge levels of the saccular units are not always balanced [2], and hence $F_{z_0} \neq 0$. This would lead to a deviation from a roll angle ρ of 90°, if the person intends to lie horizontal, since then, according to the theory of postural control worked out in [3] and [4]:

$$\hat{z} = F_{z_0} + F_{z_1} g \cos \rho = 0 \tag{3}$$

and hence the self-adopted angle $\rho_{(90)}$:

$$\rho_{(90)} = \arc\cos\left(-\frac{F_{z_0}}{F_{z_1} g}\right). \tag{3a}$$

The imbalance of the saccular resting discharge levels would explain the small but often significant deviations of a person's *mean* roll angle $0.5(\rho_r - \rho_l)$ from 90° shown in Fig. 4C. But the right-left bias evident in Figs. 4A and B, as well as the bilateral bias of the respective β values, must have other causes, e.g. small deviations of the labyrinth's from the eyes' Y-axes, or bilateral asymmetries of postural reference setting, of visual angular information, or of ocular counter-rolling and its efference copy. The theory makes it possible to differentiate between them by straightforward test procedures, which shall not be treated in this report though. At any rate, the functional organisation of the otolith system envisaged above allows to determine the direction of the subjective zenith by addition of the respective orthogonal components of the two vectors: In the case of pure roll, as in Fig. 1, this leads to

$$\tan \beta = \frac{y_{\mathrm{UTR}} + y_{\mathrm{IDIO}}}{z_{\mathrm{SACC}} + z_{\mathrm{IDIO}}} = \frac{\frac{1}{N}\hat{y} + M \sin \mu \sin \xi}{\frac{1}{N}\hat{z} + M \cos \mu} \tag{4}$$

where M is the amount of the idiotropic vector, μ its angle with the Z-axis, and ξ the deviation from the X-axis of its projection into the X, Y plane. Again simplifying, here and hitherto the visu-ocular system is supposed to work veridically, e.g., in the case of Eq. (4), to provide a correct representation of the angle β, thereby also accounting for the effect of ocular counterroll. With perfect bilateral symmetry ($F_{y_0}=F_{y_2}=0$; $\xi=0°$) we have

$$\tan\beta=\frac{\frac{1}{N}F_{y_1}g\sin\rho}{\frac{1}{N}(F_{z_0}+F_{z_1}g\cos\rho)+M\cos\mu}. \tag{4a}$$

Note that the gravity components are *normalized* by a factor N

$$N=\sqrt{\hat{x}^2+\hat{y}^2+\hat{z}^2} \tag{5}$$

with $\hat{x}$ being the utricular $\hat{x}$ component computed exactly like the other two, yet this time with respect to the receptor's orientation to the X-axis. The typical, inversely sigmoid shape of the curve measured under the paradigm of Fig. 1, results from Eq. (4a) if F_{y_1} be larger than F_{z_1}. Quite reasonable approximations are obtained with $F_{z_1}/0.5(F_{y_1}+F_{x_1})\approx 0.6$. This is indeed within the order of magnitude of the relation between the number of receptors on the saccule to that of the utricle, viz. $\approx 19000/33000=0.58$ [9]. An example of the postulated relations is given in Fig. 5, using an adaption to the data of Fig. 1, which also takes the tilt of the maculae and their response non-linearities into account.

The theory also predicts that if gravity is increased beyond $9.81\,\mathrm{m\cdot s^{-2}}$ in the human centrifuge, changes in line settings ($\Delta\beta$) are smallest or (in the special case of $F_{x_0}=F_{y_0}=F_{z_0}=0$, as in Fig. 5) absent at roll angles near or (in the special case of Fig. 5) precisely at $\rho=0°$, 180° and $\pm 90°$ relative to the resultant force direction. What happens in between these positions will depend on the non-linearities of the gravity components, particularly on one found by Fernandez and Goldberg [2] in the utricular and saccular receptors of the squirrel monkey, which limits the range of impulse rates on the excitatory as well as on the inhibitory side. This phenomenon may be even enhanced by the subsequent summation process, and thus must be accounted for in Eqs. (1) and (2) by functions which are apt to describe the sigmoidal dependency of the impulse rates on the shear force found by the two authors. If the effect of this non-linearity is more pronounced in the saccular $\hat{z}$ component than in the utricular $\hat{y}$ component, the β curves of Fig. 1 would tend to bulge in opposite directions between the orthogonal roll positions (Fig. 5). Just that has been found by Schöne and Parker [20], and Schöne, Parker and Mortag [21]. Hence in general (for details see [28])

$$\hat{y}=F_{y_0}+sg(\sin\rho)\sum^{n}F_{y_n}|g\sin\rho|^{nu} \tag{1a}$$

and

$$\hat{z}=F_{z_0}+sg(\cos\rho)\sum^{n}F_{z_n}|g\cos\rho|^{ns}. \tag{2a}$$

Also, the theory yields a prediction of what would happen under zero g conditions, as in orbiting spacecrafts. The numerator of Eq. (4a), above, would then be zero, whereas the denominator becomes $M\cos\mu+F_{z_0}/|F_{z_0}|$. Since $M\cos\mu$, in all Ss so far, has been found to range between 0 and +1, β would be zero, if F_{z_0} is positive. If F_{z_0} is negative, however, β becomes 180°, that is, the SZ lies caudad (toward $-Z$), and the astronaut would feel "upside down", when no other, e.g. visual or tactile cues are available. The situation is supposed to be very labile, if F_{z_0} be near zero. The phenomenon seems indeed to have been observed by several Russian astronauts [31, 32]. The SZ of an astronaut in orbit should thus largely be determined by the functional polarization pattern of his saccule, i.e. by the mean difference between the resting discharge rates of the units polarized toward $-Z$ or $+Z$, respectively (see Fig. 7). If SZ computation and postural control are indeed served by the same gravity input(s), as provisionally assumed above, the sign of F_{z_0} might be verified by way of the S's self-adopted horizontal position (cf. Eqs. (3, 3a)) – at long last permitting the preselection of space flight candidates who could be expected to feel allright at least statically.

This report will refrain from a more detailed presentation of the gravity part of the theory though, and may now turn to that of the idiotropic vector.

The Idiotropic Vector

Here, by contrast with the area just traversed, we enter unknown territory calling for further experimental exploration. If the idiotropic vector does indeed shift the subjective zenith towards the direction of the person's long axis, it should also manifest itself, if the S is rotated about another axis, e.g. *pitched* backwards, and then asked to indicate the direction of the zenith. In the following experiment, a translucent sphere (of $\varnothing = 14{,}4$ cm) covered all over with small luminous dots may be orbited at a distance of 90 cm around the Ss' *Y*-axis, that is the axis running through the centres of the eyes. The test paradigm is analogous to that of Figs. 3 and 4: The Ss, now lying on their backs on the board of Fig. 2, are first asked, starting alternatingly from various pitched up or down positions, to adopt a horizontal position in the dark, and then open their eyes and set the dotted sphere such that "a drop of water falling down from its centre would hit them right between their eyes". This instruction naturally instigated good fixation. In order to meaningfully compare the results of this experiment with those of the first, one has to define the *X*- and *Z*-axes of the head in an interpretable way. Instead of using an arbitrary anatomical reference, we asked the Ss while standing, or sitting on a stool, with eyes closed, to assume a perfectly upright head position. The *Z*-axis is defined as that head axis which is then held vertical. This gives us the advantage of being able to rigorously interpret the results although at the risk of increased errors in the data (the first, because then the gravity components should be at $\hat{x} = \hat{y} = 0$, $\hat{z}/N = 1$!). As shown in Fig. 8, essentially the same happens as in the analogous roll experiment: Small deviations from the intended 90° pitch position contrast with considerable deviations of the sphere from physical zenith.

That the deviations from veridicality at the 90° roll ($\rho = 90°$) and the 90° pitch position ($\nu = 90°$) are correlated is shown in Fig. 9 where they are plotted on the abscissa and the ordinate, respectively, yielding a line of best fit at $\delta_{\text{pitch}} = 1.3\,\delta_{\text{roll}} - 2°$, and a correlation coefficient of $r = 0.88$. As a further consequence, the visu-ocular information must indeed be rather veridical, which is all the more remarkable, because it originates mainly from the retina in roll, whereas mainly from a representation of the eye position (probably an efference copy) in pitch. In the latter case, the (forward) deviation γ of the SZ from the S's *Z*-axis is obtained from

$$\tan\gamma = \frac{\frac{1}{N}\hat{x} + M \sin\mu \cos\xi}{\frac{1}{N}\hat{z} + M \cos\mu}. \tag{6}$$

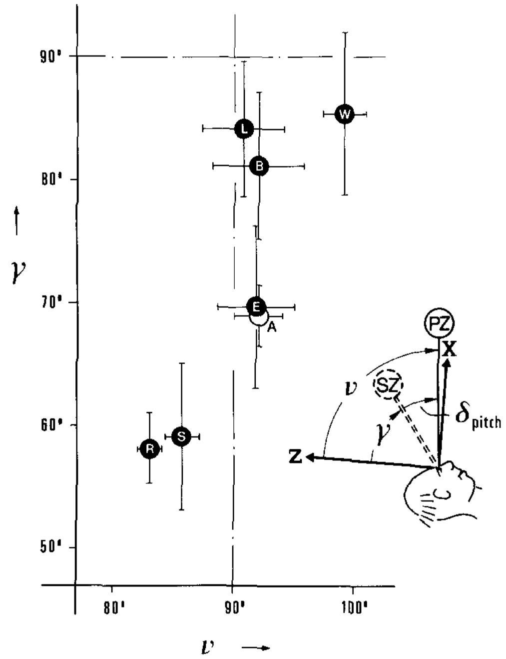

Fig. 8. Determination of self-adopted 90° pitch direction; apparatus and procedure as in Fig. 2, but with Ss lying on their backs. After having assumed a subjectively horizontal position (on the abscissa: angle ν, see inset; PZ: physical zenith) they are asked to set a sphere covered with luminous dots into their subjective zenith (SZ). Its deviation γ from the Ss' *Z*-axis is shown on the ordinate. Brackets: standard deviations

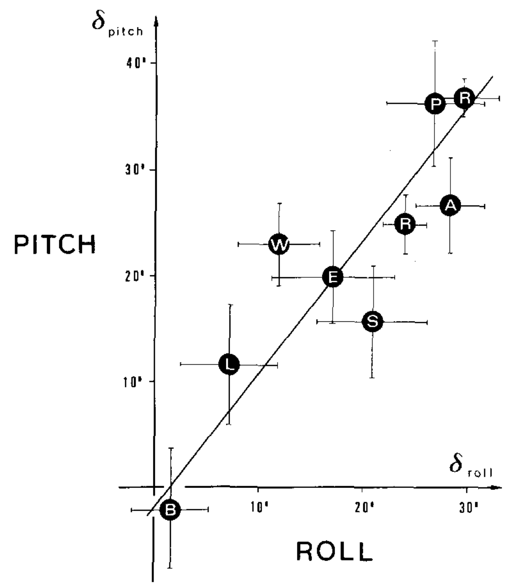

Fig. 9. Deviation δ_{pitch} (see inset of Fig. 8) plotted over the deviation δ_{roll} (see inset of Fig. 3) in 9 persons (staff members) at fixed head-and-body positions of $\nu = 90°$ and $\rho = 90°$, respectively. Brackets: standard deviations, diagonal line: line of best fit (least sum of squared distances)

Note that γ (Fig. 8) is the complementary angle of the eye elevation, when the S fixates the sphere's centre. In some Ss these tests have been done since two years. Fig. 10 shows for three of them that amount and rank order are well preserved. We may thus presume that the amount of the idiotropic vector is a personal constant indeed.

Where may it originate? As already proven, it is not a part – at least not an inseparable one – of the gravity systems. Otherwise it would also manifest itself in postural control. It may, however, be a part of the visu-ocular system instead, because Eq. (4a), with $\mu=\xi=0°$, may be thought of as resulting from two separate operations within the CNS, namely:

$$\left[\sin\beta \frac{1}{N}(F_{z_0}+F_{z_1}\, g\cos\rho)-\cos\beta\frac{1}{N}F_{y_1}\, g\sin\rho\right] + [M\sin\beta]=0. \qquad (7)$$

The first terms set in square brackets represent the well-known bi-component cross-multiplication, which is an adequate solution to a task of this kind, i.e. a coordinate transformation, anyway [4, 22]. Yet the last term may represent a purely visual turning tendency, to be summed up with the result of the former. To check up on the latter possibility, it was tested whether the idiotropic vector could also be demonstrated when a different sensory system was employed for indicating the subjective zenith. In the experiment, the pitch set-up was used. Instead of the dotted sphere, however, a handy knob could be orbited about the S's Y-axis along a hemicircular railing in the S's median plane, and centered at the S's head. The Ss could grasp it with a hand of their choice and set it to their SZ. In order to ensure equity with the respective visual experiment, special care had to be taken that the proprioceptors of the hand and arm were prevented from getting any information about the direction of *gravity*, while preserving their ability to measure arm and hand *position*. To that end the arm was suspended by means of leather cuffs and spiral springs alternatingly to one of two points at the room's ceiling, thus not only overcompensating the weight of the arm but also misdirecting the force vector in the median plane. In Fig. 11 the results of this test, plotted over the results of the respective visual one, demonstrate a near perfect coincidence. Note that the determination procedure of the Z-axis cannot increase the variance here, because the axis, though possibly somewhat misplaced, is identical for each S in both sets. The line of best fit is at $\delta_{\text{pitch haptic}}=0.78\,\delta_{\text{pitch optic}}+5°$ and the correlation coefficient $r=0.99$. If the arm's weight was not compensated, the slope of the regression line decreased considerably, yet the correlation was preserved, excluding, by the way, that haptic gravity messages, if acting in this case, are *jointly* normalized with the gravity inputs acting in the case of Fig. 11. The result indicates that *the idiotropic vector is not part of a specific sensory system but rather a central*

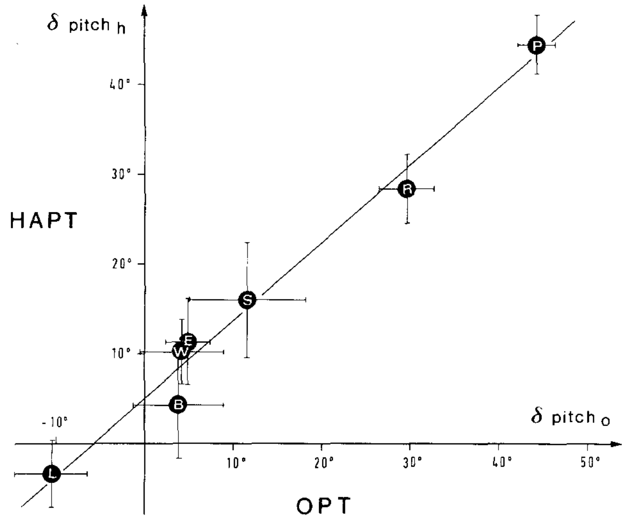

Fig. 11. The relation of the haptic zenith to the visual zenith in 7 Ss (staff members). The Ss, lying supine ($\nu=90°$), are asked to set a knob, sliding on a circle about the Ss' Y-axis in the X, Z plane, to their SZ. The weight of the arm and hand is overcompensated (see text). Abscissa: angle $\delta_{\text{pitch o}}$ as defined in Fig. 8, ordinate: the analogous angle $\delta_{\text{pitch h}}$, with the knob in the place of the visual display, lines as in Fig. 9

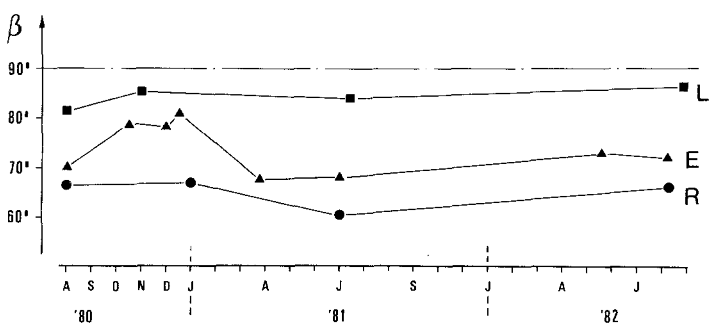

Fig. 10. Subjective vertical of 3 Ss (staff members) during 2 years. The angle β is determined in the set-up of Fig. 2 at a fixed head-and-body position of $\rho=90°$

nervous agent involved whenever the subjective vertical is to be computed.

This opens the question whether the idiotropic tendency is merely a side-effect of the neural mechanism which works out this coordinate transformation or rather part of an autonomous system of orientation which competes with the gravity system for dominance over a common reference. Some indications for the latter have turned up in recent pilot experiments, where head and body were set at an angle (Fig. 12). The line, now made rotatable about *two* orthogonal axes, was then set by the Ss, as if the direction of the idiotropic vector would deviate from the Z-axis of the head in the direction of the Z-axis of the trunk. The conclusion is that the idiotropic vector results from an interaction of (at least) two components, one leading to a tendency to shift the SZ into the direction of the head's the other into the trunk's Z-axis. Because the trunk's relative position may be altered *passively*, the necessary information about the angle between head and trunk is expected to be procured by proprioceptors, rather than by an efference copy. Furthermore, if in a supine position of the trunk the head is pitched backwards by 90° such that its Z-axis points downwards, some Ss acknowledge *two* positions of their subjective zenith, with a zone of ambivalence between the two points. Hence one has to reckon with non-linearities in the interaction of the two components (and possibly even in their joint interaction with the gravity systems). Yet this does not lead in such situations to a flip-flop alternation between two zenith positions each impressing with the same "consummate clarity and unquestionable self-evidence", but rather to a diffuse uncertainty of where exactly the SZ may be. Such "flat zones" are readily produced, if, in the mathematical theory, the first harmonic terms are replaced by Fourier series with exponentially declining amplitudes, a pattern which has recently been found in the orientation systems of several animals [4, 23–25].

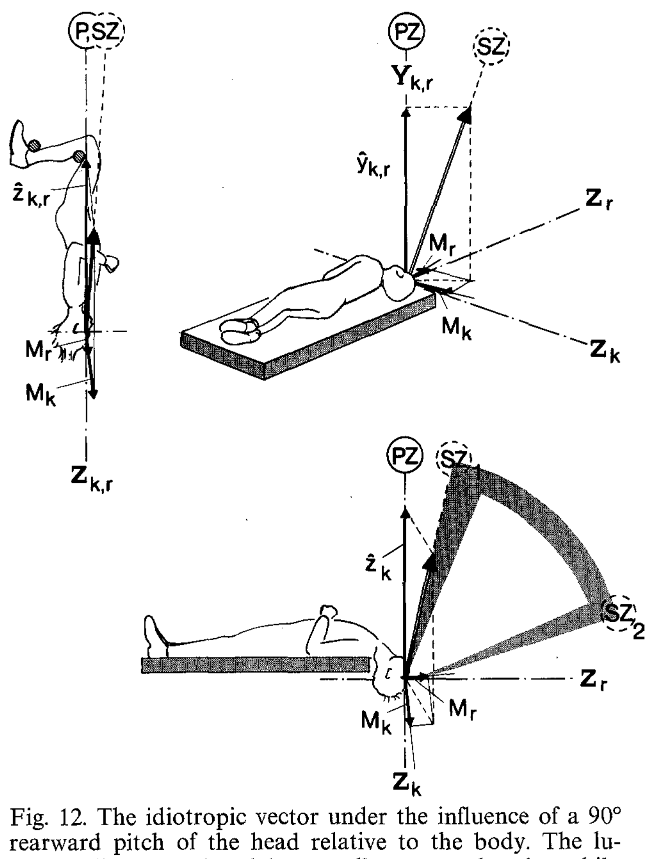

Fig. 12. The idiotropic vector under the influence of a 90° rearward pitch of the head relative to the body. The luminous line is replaced by a well contoured rod, mobile about two orthogonal axes in front of a homogeneously white planetarium cupola. The Ss are placed in fixed positions as shown. All symbols as in Figs. 3, 5, 8; index r: trunk axes, index k: head axes, $M_{r,k}$: trunk or head component of the idiotropic vector, respectively. The three pictures show the settings of one S (E in Figs. 4, 8–11), who reported the bifurcation phenomenon mentioned in the text

Many problems of the subjective vertical are still to be solved which are not even touched upon in this report, for instance the problems of its dynamics, and those we encountered when the person was yawed around her, horizontal, Z-axis from a 90° roll to a 90° pitch position. The projection of the subjective vertical into the visual world then ought to travel, as it were, from the fronto-parallel plane – as in pure roll – into the median plane – as in pure pitch – through a three-dimensional visual space the metric of which will determine where the person will set the line. The deviations from Euclidian orthogonality of the, according to the theory of Luneburg [26, 27], Riemannian, hyperbolically curved visual space, which we have neglected in the roll and sidestepped in the pitch case, would then have to be incorporated into the theory, and empirically tested by the subjective experience of our persons.

To end then on the note of our beginning, since humans are not only conscious of the world but also of themselves we asked our persons to size up their own achievements in these tests. Surprisingly enough their judgements of their prowess turned out to be inversely correlated to the variance of their results. The S.D.s of the line settings were on average three times as large as those of the self-adopted 90° tilts (cf. Figs. 3 and 4). Unanimously, however, while convinced of their excellence in the first case, they were rather doubtful about their achievement in the second. Thus even in this facet of his subjectivity, man appears as a creature, whose mind underrates the humble services of his bodily feelings while naively taking at face value what the believes to see, unaware of being deceived, as it were, by the workings of a machinery which toils in the interest of survival but not in the service of truth. Indeed, if at least this theory be true, the idiotropic vector helps to reduce the over-compensatory (cf. Fig. 5) effect of the inequality of the two sets of otolith maculae, when the head is not too far from its usual upright position. And forsooth, by just then maximizing the resultant vector length, it does stabilize man's confidence in the stability of his world.

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