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Motion sickness: Only one provocative conflict?

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ABSTRACT: In reviewing the various forms of motion sickness, the classic sensory rearrangement theory has been redefined by demonstrating that only one type of conflict is necessary and sufficient to explain all different kinds of motion sickness. A mathematical description is provided from the summarizing statement that "All situations which provoke motion sickness are characterised by a condition in which the sensed vertical as determined on the basis of integrated information from the eyes, the vestibular system and the nonvestibular proprioceptors is at variance with the subjective vertical as expected from previous experience." © 1999 Elsevier Science Inc.

KEY WORDS: Motion sickness, Subjective vertical, Visual-vestibular interactions, Modeling.

INTRODUCTION

The so-called sensory rearrangement theory on motion sickness developed by Reason and Brand [35] is widely accepted today. The basic idea is that all situations that provoke motion sickness are characterized by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the nonvestibular proprioceptors are at variance either with one another or with what is expected from previous experience. Reason and Brand specify two main categories of motion cue mismatches according to the sensory systems involved: an intersensory conflict dealing with a visual-vestibular mismatch and an intrasensory conflict for a canal-otolith mismatch. They further classify these mismatches into two types of conflict: a type 1 conflict, when both systems signal simultaneously contradictory motion information, and a type 2 conflict, when one system signals motion in the absence of a corresponding signal from the other sensor. Guedry [22] extends the two mismatch categories with a third category dealing with a vestibular-proprioceptor mismatch.

Despite the many examples given by Reason and Brand [35] or by Griffin [20] of forms of motion sickness belonging to certain types and categories, it remains difficult in practice to classify a particular provocative motion condition into only one of these conflict categories. The heuristic motion sickness model as described by Oman [33] provides a mathematical basis for the above-described components of the sensory rearrangement theory on motion sickness. In view of the topic of this article, the point of interest in Oman's model is that motion sickness is related to the vector difference between a vector representing all the available afferent sensory information and a vector representing the expected sensory information. When this difference vector grows,

the chance of motion sickness and the severity of the motion sickness will increase. With his choice of the conflict vector, Oman pinpoints the conflict to a discrepancy between the sensed and expected information of all individual sensors. This is in agreement with the description as given by Benson [1]. Intersensory conflicts as described by Reason and Brand do not contribute to a conflict so defined. The same is true for the rules provided by Stott [40].

Although we agree that most of the examples of the different conflicts as described by Guedry [22] may lead to disorientation and motion illusions, it is our experience that motion sickness is primarily provoked in those situations where the determination of the subjective vertical, the internal representation of gravity, is challenged. This can be illustrated by two examples.

First, after long-duration centrifugation, only head movements that change the orientation of the head relative to the gravity vector provoke motion sickness. In an upright sitting subject, roll and pitch movements of the head provoke motion sickness, whereas yaw movements elicit motion illusions but no motion sickness. With the subject in supine position, yaw and pitch head movements are provocative, but roll motion is not [7]. This illustrates that sensory mismatches may induce motion illusions but only provoke motion sickness when the determination of the subjective vertical is at stake.

A second example concerns the studies on optokinetic circularvection. Despite the absence of corresponding vestibular information, motion sickness is only occasionally observed during sudden onsets of surround motion. This is the experience of several European research groups using the large optokinetic drums manufactured by Tönnies (Freiburg in Br.). Motion sickness incidence in this type of experiments is estimated to be lower than 1% (Brandt, Probst and Bles, personal communication). The almost complete absence of motion sickness seems to be in conflict with the sensory rearrangement theory, because the optokinetic stimuli create clear differences between the sensed and expected sensory information in terms of the Oman model. We came to the conclusion that the low incidence of motion sickness is due to the fact that in these drum experiments the stimuli are neutral with respect to gravity. Of course, during optokinetic circular motion stimulation head tilt provokes motion sickness, the so-called pseudo-Coriolis effects [12], but then the subjective vertical is at stake.

These examples led us to redefine the sensory rearrangement theory on motion sickness: "All situations which provoke motion sickness are characterised by a condition in which the sensed vertical as determined on the basis of integrated information from

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the eyes, the vestibular system and the nonvestibular proprioceptors is at variance with the *subjective vertical* as predicted on the basis of previous experience."

"SUBJECTIVE VERTICAL CONFLICT" MOTION SICKNESS MODEL

The subjective vertical conflict motion sickness model, henceforth called the SV-conflict model, is shown in Fig. 1. The model is an extension of the Oman model. The principles of the Oman model are shown in thin lines in Fig. 1, and for a detailed description reference is made to Oman [33]. In short, the Oman model states that, based on the desired position \mathbf{x}_d , muscle activity (m) is generated, leading to a position \mathbf{x} due to the body dynamics (B). This signal, together with the external noise n_e , is detected by the senses (S), resulting in sensory information \mathbf{a} . Oman also assumes that an internal model that consists of the same components (indicated with a hat) computes the expected sensory information $\hat{\mathbf{a}}$. Differences (the vector \mathbf{c}) between the vectors \mathbf{a} and $\hat{\mathbf{a}}$ are calculated, of which a weighted (K_c) amount is fed back into the system. In this way, an optimal estimate of the actual position can be obtained. Apart from the position \mathbf{x} , it is obvious that the other motion parameters like velocity and acceleration should be considered as well. According to Oman, the difference vector \mathbf{c} is the origin of motion sickness.

The SV-conflict model extends the Oman model with a network V that constructs the sensed vertical, \mathbf{v}_{sens} , based on the incoming sensory information. Similarly, in the internal model a network \hat{V} is added that constructs the expected vertical, $\hat{\mathbf{v}}$ or \mathbf{v}_{exp} , based on previous experience and expectation. The difference vector \mathbf{d} between \mathbf{v}_{sens} and \mathbf{v}_{exp} is used to update \mathbf{v}_{exp} . The so-updated \mathbf{v}_{exp} will henceforth be called the subjective vertical \mathbf{v}_{subj} . However, the measurement of the subjective vertical as an experimental parameter may depend on the psychophysical procedure. For instance, the manual settings of an unseen bar may not necessarily lead to the same results as the visual judgment of a luminous line. To account for this, we introduced a transfer module F , the output of which is the measured subjective vertical, or \mathbf{v}_{meas} .

In contrast to Oman, we assume that it is not vector \mathbf{c} that generates motion sickness but instead vector \mathbf{d} , i.e., the vector difference between \mathbf{v}_{sens} and \mathbf{v}_{subj} (Fig. 1). This article concentrates on the type of conflict that may lead to motion sickness. The detailed description of the modules behind vector \mathbf{d} that lead to motion sickness will therefore remain beyond the scope of this article.

The computation of the sensed vertical \mathbf{v}_{sens} in module V is proposed to take place according to the scheme shown in Fig. 2 [5,6]. The computation of \mathbf{v}_{sens} is part of the signal processing of the sensory systems like the vestibular, the visual and the somatosensory system that all provide information on spatial orientation.¹ To obtain only one unique spatial orientation, it is assumed that all this sensory information is integrated to obtain basically three signals, indicating the sensed rotation (\mathbf{r}_{sens}), the sensed translation (\mathbf{t}_{sens}) and the sensed vertical (\mathbf{v}_{sens}).

The integration of rotatory motion information to obtain \mathbf{r}_{sens} is rather straightforward, because the sensory systems provide complementary information [see for instance 4,41]. A bigger problem for the central vestibular system is to extract \mathbf{v}_{sens} out of the sensed gravito-inertial force vector. In view of normal human movements and locomotion, it was hypothesized that low-pass filtering of the gravito-inertial force vector could preserve gravity. This is a sen-

sible approach, provided that the angular motion information \mathbf{r}_{sens} helps to compensate for the consequences of fast head tilts. Mathematically, this compensation is accomplished by a transformation T of the coordinate frame with the otolith vectors, over the angle of the head tilt indicated by \mathbf{r}_{sens} . Such a manipulation keeps the input to the low-pass (LP) filter unchanged, the sensed vertical after the head tilt being determined initially by the rotatory motion information due to the inverse transformation T^{-1} as shown in Fig. 2. If the change in direction of the gravito-inertial force vector as sensed by the otoliths does not correspond exactly to the angle as indicated by the signal \mathbf{r}_{sens} , the LP filter ensures that the otoliths finally determine \mathbf{v}_{sens} . This is a similar modeling approach as used previously [16,29]. Recently, one of us showed that the above-described module V is mathematically even identical to the Glasauer model [10]. The LP filter fits experimental evidence of a slowly developing percept of tilt during sustained horizontal acceleration [14,39]. In principle, \mathbf{t}_{sens} is now the difference between the gravito-inertial force vector and \mathbf{v}_{sens} .

Visual structures that contain direct information about what is horizontal or vertical also determine \mathbf{v}_{sens} . Because these effects may be almost instantaneous, this interaction is supposed to take place after the LP filter. For the arguments used here, the location and nature of this interaction are not immediately relevant.

It is hypothesized that the internal model uses the same computation rules to calculate \mathbf{v}_{exp} or \mathbf{v}_{subj} . As mentioned above, the difference vector \mathbf{d} , which should somehow serve to adjust \mathbf{v}_{subj} , is thought to trigger motion sickness and to be correlated to the incidence/severity of motion sickness. Because \mathbf{d} is a vector, not only its magnitude but also its direction may affect the severity of motion sickness.

ONLY ONE CONFLICT?

Motion sickness characteristics are different among the various forms of motion sickness [26]. Despite these differences we believe that all types of motion sickness have one underlying conflict in common, which is the conflict about the subjective vertical. So the main question is whether the conflict categories as described by several authors [20,22,33,35] can be restricted to only this conflict, or, in other words, is the SV-conflict theory sufficient to account for the different forms of motion sickness? To answer this question, we focus on the main difference between the SV-conflict theory and the more general sensory conflict theory first and thereafter review the most common types of motion sickness from the viewpoint of the SV-conflict theory.

SV-Conflict Theory Versus General Sensory Rearrangement Theory

Motion sickness has often been explained as the consequence of passive motion because then the expected signals $\hat{\mathbf{a}}$ will be different from the sensed ones \mathbf{a} , increasing the vector \mathbf{c} . However, passive motion does not necessarily influence the magnitude and the direction of \mathbf{v}_{subj} , so \mathbf{d} is not always increasing. This is an important difference between the two concepts, because this might explain why people get sick in one situation and not in the other, despite the fact that \mathbf{c} is large in both situations. This is illustrated in the following example. What happens to the vectors \mathbf{c} and \mathbf{d} when a subject is given a sudden push? Before the push it may be assumed that \mathbf{v}_{sens} and \mathbf{v}_{subj} are aligned. If the push is unexpected, the internal model would not immediately foresee any particular change in the incoming sensory information $\hat{\mathbf{a}}$. Therefore, \mathbf{v}_{exp}

¹ Of course, other sensory systems, like, for instance, the auditory system, may provide corresponding information about spatial orientation that should add to the integration process as well.

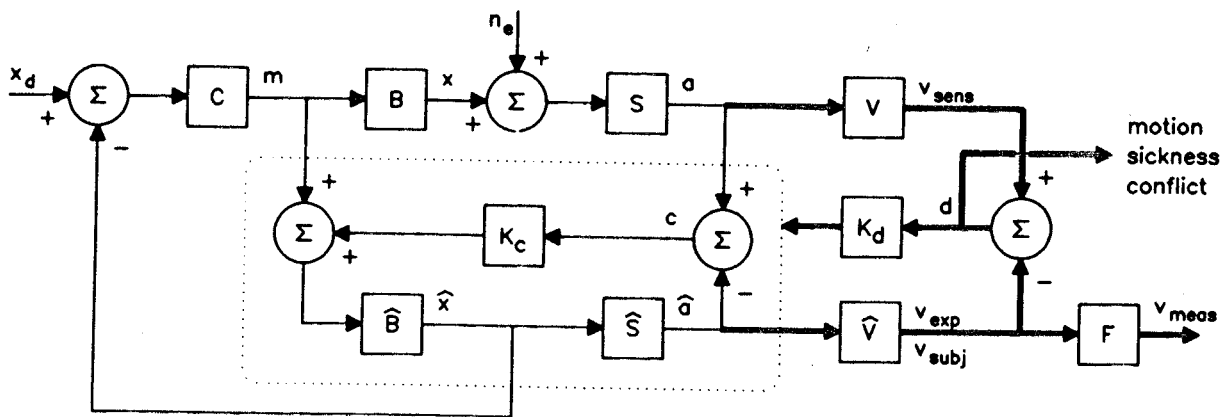


FIG. 1. The subjective vertical conflict motion sickness model as described by Oman [33], extended with the modules that are necessary for the computation of the subjective vertical (thick lines). The vector \mathbf{d} is considered to be the conflict vector for generating motion sickness.

would not immediately change. After the push, many sensory systems will immediately signal motion \mathbf{a} , which means that the vector \mathbf{c} increases dramatically, provoking motion sickness according to the general sensory conflict theory. However, the direction

of gravity information as encoded in \mathbf{v}_{sens} will be hardly affected, if at all, because it is not affected by such high-frequency linear motion information (Fig. 2). So \mathbf{v}_{sens} will not differ too much from \mathbf{v}_{subj} , keeping \mathbf{d} minimal, and the subject should not get motion

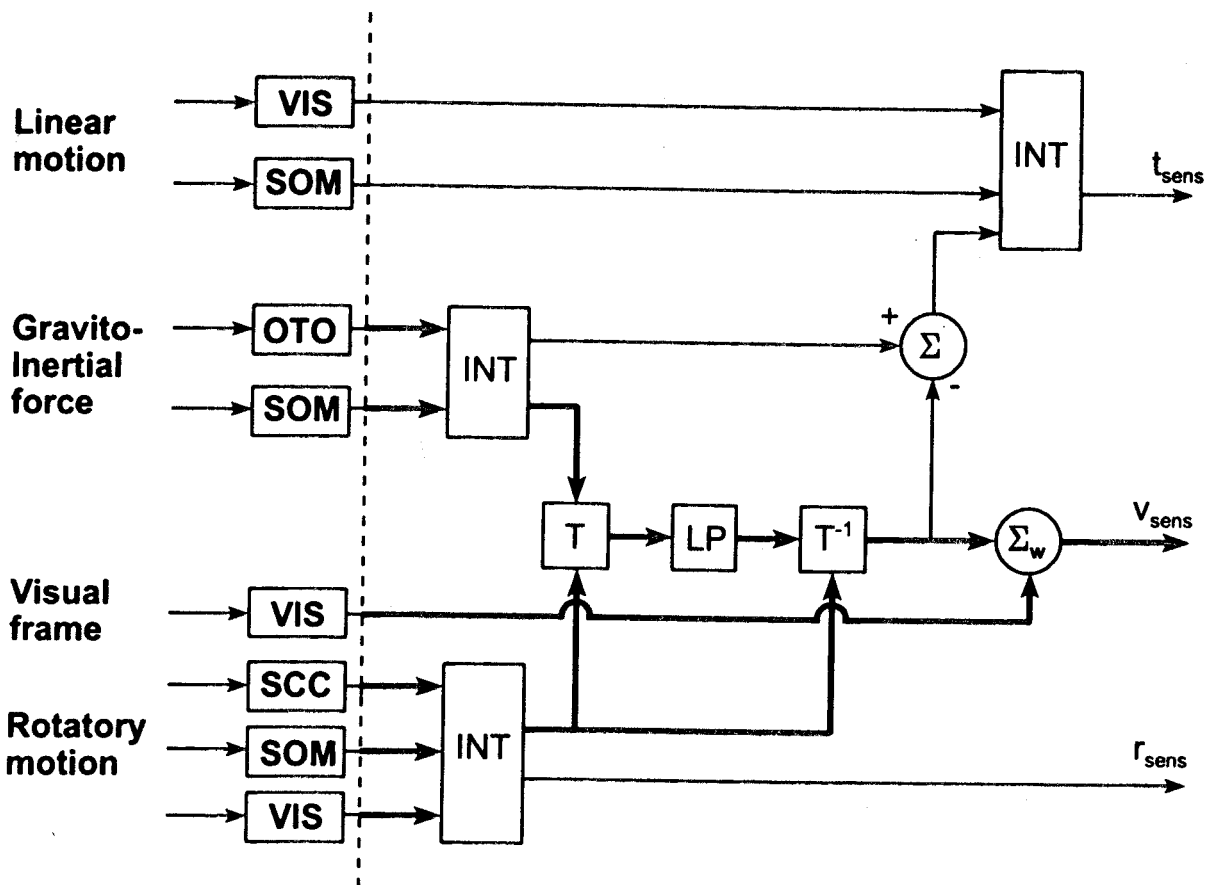


FIG. 2. Global scheme for computation of the signals indicating translation, rotation and the vertical. To illustrate how this diagram connects to the main model shown in Fig. 1, the dotted line is drawn to mark the input side for module V . Everything to the left of the dotted line represents vector \mathbf{a} in Fig. 1; everything to the right represents module V . The thick lines indicate the components involved in the calculation of the subjective vertical. See text for further details.

sick according to the SV-conflict theory. We know that this is the case indeed. The subject is not motion sick, only angry about the push. The vector \mathbf{c} is certainly important to guarantee appropriate countermeasures to prevent falling.

This example illustrates the main difference between the two motion sickness theories: Large differences between sensed and expected sensory information may be present without provoking motion sickness as long as the sensed vertical \mathbf{v}_{sens} based on the detected motion remains aligned with the subjective vertical \mathbf{v}_{subj} . In the subsequent analysis of the different types of motion sickness, this argument will often return.

Coriolis Effects and Consequences of Rotation About the Vertical Axis

The nausea provoked by making head movements during yaw motion is known as the Coriolis effect, and the nausea as a consequence of head movements during optokinetic surround motion is known as the pseudo-Coriolis effect. Guedry [21] explained the Coriolis effect as the consequence of the conflict between the head tilt indicated by the otolith and neck receptors and the direction of the angular velocity vector as sensed by the canals. Detailed data on the incidence and the severity of motion sickness are available from many experiments on Coriolis and pseudo-Coriolis effects. For instance, it is well known that tilt of the head on the shoulder in darkness during constant velocity rotation is very provocative. However, dependent on the sensed angular velocity vector present just before the head tilt, the Coriolis effect may be suppressed or enhanced: The more the sensed resultant angular velocity vector after the head tilt differs in direction from the gravito-inertial force vector, the stronger the nauseogenic effect [23]. Similar observations have been reported for visual-vestibular interactions [12] and for somatosensory-vestibular interactions [3].

This is in perfect agreement with the SV-conflict theory on motion sickness. By definition, the internal model always expects that \mathbf{v}_{subj} remains aligned with gravity, independent of whether it assumes the body as turning or stationary. This seems logical and can be demonstrated mathematically [4]. However, when the rotation vector \mathbf{r}_{sens} is not aligned with gravity, \mathbf{v}_{sens} will deviate from gravity. According to the model as shown in Fig. 2, \mathbf{v}_{sens} will then differ from \mathbf{v}_{subj} , so \mathbf{d} will increase. Note that \mathbf{v}_{sens} is not affected as long as rotation takes place about the gravitational vertical (for a more detailed description see [4]).

Guedry and Benson [23] and the SV-conflict theory implicitly state that one should not get sick from rotation about an Earth-vertical axis. Most researchers would accept that these rotations are not very provocative indeed. However, as mentioned earlier, in some experimental paradigms dealing with rotations about an Earth-vertical axis, motion sickness can be evoked. But in these conditions other sensory aspects are involved as well. For instance, motion sickness incidence is high when retrieving digits from a matrix filled with digits presented head stationary in front of a subject who is rotated sinusoidally about the vertical axis, whereas the incidence is small when a simple visual display is used [22]. De Graaf, using only a horizontal array of digits, did not find any motion sickness in a (unpublished) pilot study with many pilot students. Whether looking up or down changes the apparent level of the horizon, just as looking aside affects the straight-ahead, remains to be established firmly, but that would certainly influence the determination of \mathbf{v}_{sens} as can be derived from Fig. 2.

It is remarkable that the laboratories working with the large optokinetic drums that prevent any view at the outside have so little motion sickness incidence with only optokinetic motion. Laboratories working with other optokinetic devices find much higher motion sickness incidences, although the stimulus duration

should be mostly about 15 min and motion sickness incidence increases with drum rotation [e.g., 15,25,38]. Here too a reason could be that the subjects, inadvertently, tend to find a stable reference frame outside the drum by looking downward to the floor or upward to the ceiling, even without making head movements (head movements would provoke motion sickness anyhow, but that is not the point here). To prevent motion sickness, it is also imperative that the optokinetic drum moves exactly around the vertical axis with exact vertical stripes and is not swinging at all, because that would influence the sensed motion path and consequently the vertical. These restrictions certainly apply to the Tönies drums.

Another point of interest is how the subject is positioned: Is the head exactly in the center of rotation during sinusoidal rotation? Otherwise centrifugal forces may be introduced, affecting \mathbf{v}_{sens} , because the gravito-inertial force vector is no longer aligned with the rotation axis. This may provoke motion sickness according to our SV-conflict theory. Rotating chairs for clinical vestibular tests mostly do not have the head exactly in the center of rotation. Further research is needed to clarify these observed discrepancies.

Sea Sickness

The most extensive experimental data sets on sea sickness have been gathered by O'Hanlon and McCauley [32], McCauley et al. [30] and Griffin [19]. O'Hanlon and McCauley performed a series of experiments with the ship motion simulator from the Naval Biodynamics Laboratory in New Orleans. They found that the vertical motion was the only motion component that contributed to the motion sickness incidence and described this incidence mathematically as a function of amplitude, frequency and exposure time for pure vertical sinusoidal motion. Lawther and Griffin [28], summarized by Griffin [19], explored the motion sickness incidence for real ship motion. These last authors also found that the vertical motion of the ship corresponded best with the motion sickness incidence.

It has been shown by Bos and Bles [11] that the SV-conflict model predicts the data set of O'Hanlon and McCauley. Here it should be mentioned that the low-pass filter in the V module plays an essential role to accomplish that the frequency range around 0.2 Hz is the most provocative. This is important because this neither follows straightforward from the Oman model [33] nor from Griffin's model [19].

Wertheim et al. [42] showed that combinations of heave motion with pitch and roll motion considerably increase the motion sickness incidence. They, for instance, observed severe motion sickness in approximately half of their subjects when they were stacking crates (involving a lot of head movements) in the TNO ship motion simulator running real ship motion profiles. The heave motion alone of this profile would have resulted in a motion sickness incidence of maximally 1% according to McCauley et al. [30] and of maximally 6% according to Griffin [19]. So the incidence of sea sickness may be underestimated if smaller ships with more pitch and roll motion are considered. The reason for the high incidence in the study of Wertheim et al. is that the rather low frequency pitch and roll motion are not dealt with adequately by the vestibular system, leading to cross-coupled canal stimulation during head movements. In the SV-conflict model this would lead to an inadequate \mathbf{v}_{sens} with subsequent deviations \mathbf{d} from \mathbf{v}_{subj} , similar to what happens during Coriolis effects [4]. The fact that head movements play an important role in the enhancement of sea sickness can also be derived from the advice to minimize head movements as much as possible to prevent sea sickness [2]. The common experience that sight of the horizon minimizes sea sick-

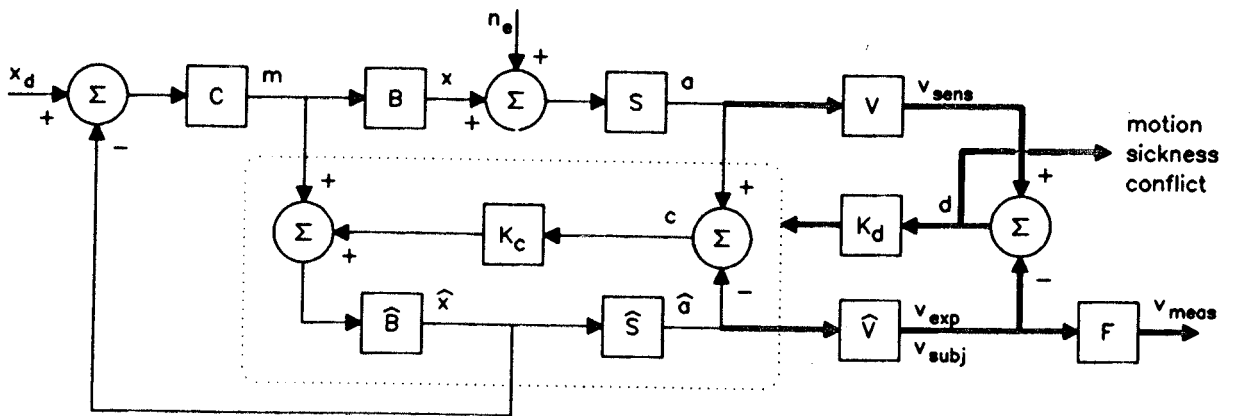


FIG. 1. The subjective vertical conflict motion sickness model as described by Oman [33], extended with the modules that are necessary for the computation of the subjective vertical (thick lines). The vector \mathbf{d} is considered to be the conflict vector for generating motion sickness.

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of gravity information as encoded in \mathbf{v}_{sens} will be hardly affected, if at all, because it is not affected by such high-frequency linear motion information (Fig. 2). So \mathbf{v}_{sens} will not differ too much from \mathbf{v}_{subj} , keeping \mathbf{d} minimal, and the subject should not get motion

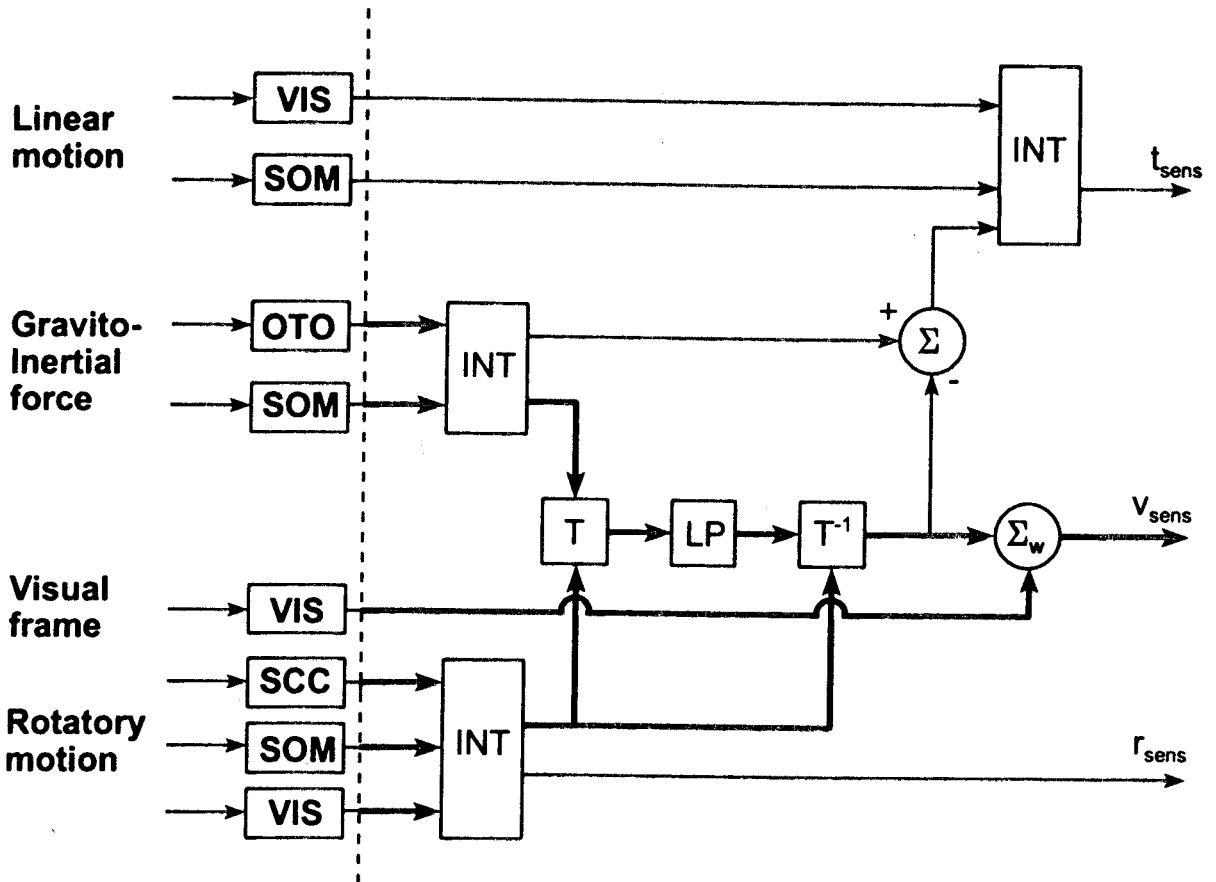


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ness is most probably due to the fact that seeing the horizon helps to keep the sensed and subjective vertical aligned.

Effects of Micro- and Hypergravity

A micro- or hypergravity load per se does not provoke motion sickness symptoms. Continuously changing the G-load level as in parabolic flight may be provocative, but head movements during the different G-levels are the most provocative [13,27]. Even during and after a centrifuge run at $3G_x$ for 1.5 h, subjects are asymptomatic as long as they remain motionless. The provocativeness of different types of head movements was investigated after such long-duration centrifuge runs. It was found that yaw head motion was not provocative at all, whereas pitch and roll head motion provoked motion sickness symptoms when they were sitting upright. Pitch motion was found to be the most provocative. However, when the subject subsequently took a supine posture, roll movements were not experienced as provocative any longer, whereas pitch head movements and now also yaw motion provoked sickness symptoms [7]. Although it is not clear how the adaptation process has influenced the different parameter settings during the G-load, it is clear that only those head movements were provocative, which changed the orientation of the head relative to the gravitational vertical. This observation was the basis for the SV-conflict theory on motion sickness.

It has been reported that during the first days of the mission, astronauts orient themselves more on the (vertical) contours of spacelab than after a couple of days. Because after some time in space vertical or horizontal has no specific meaning anymore, it is no surprise that Coriolis experiments in *SkyLab* performed after a couple of days in space proved to be not provocative at all [18]. In fact, this is in agreement with the concept that motion sickness relates to problems with the determination of the vertical only.

Air and Car Sickness

Although there are many movements of an aircraft that may cause motion sickness, aerobatics is well known as being provocative among student pilots. Without a detailed analysis it is easily understood in view of the foregoing discussion that the visual-vestibular conflicts thought to cause motion sickness according to the classic sensory rearrangement theory also challenge the computation of the subjective vertical under these circumstances. For passengers in civil transport aircraft, bumpy weather is known to provoke air sickness. Varying G-loads are the important vestibular stimuli in an otherwise stable visual surrounding. It is obvious that these stimuli easily lead to discrepancies between the sensed and the expected vertical and thus deviates \mathbf{d} from zero.

Driving uphill at night along a winding road may provoke car sickness in the passengers in the back seat. The continuously changing gravito-inertial force vector, together with the inability of the semicircular canals to appropriately signal the angular motion because of the stable visual interior of the car, will affect both \mathbf{v}_{sens} and \mathbf{v}_{subj} and subsequently provoke motion sickness according to the SV-conflict model. Linear acceleration and deceleration without appropriate view of the road ahead causes car sickness as well [34]. This is also in agreement with laboratory experiments that showed that horizontal low-frequency oscillations lead to motion sickness in a certain frequency range [17]. Most probably this is explained by the SV-conflict model in a similar way as was shown for vertical motion [11]. Intuitively, one would expect that the SV-conflict model in these cases would again predict discrepancies between \mathbf{v}_{sens} and \mathbf{v}_{subj} similar to what was described in the section on sea sickness. Without analyzing this in detail, it is obvious that the gravito-inertial force vector is varying in motion conditions that lead to car sickness, and \mathbf{d} will not remain zero. It

is feasible that the SV-conflict theory is appropriate to explain why passengers who are susceptible to motion sickness benefit from sitting next to the driver and look at the road ahead. They anticipate on what maneuvers will come next. This explains as well why drivers are never motion sick.

Simulator Sickness

Motion sickness is also encountered in simulators. It is called simulator sickness if an individual is motion sick in the simulator but the original motion did not provoke motion sickness. Simulator sickness might be due to insufficient motion capabilities of the simulator to mimic the amplitudes of the real motion. The motion characteristics of transport aircraft are such that the moving bases of transport aircraft simulators can move sufficiently to "convince" the human equilibrium system that the visually suggested motion is complemented by the appropriate physical motion stimuli. Simulator sickness is therefore not a common observation in these simulators. For highly maneuverable military aircraft (as well as for off-terrain vehicles), the motion characteristics of a moving base are often insufficient to stimulate the vestibular system "convincingly," which may result in simulator sickness. It is a common observation that experienced fighter pilots suffer more from simulator sickness than student pilots. This may be due to the fact that the experienced pilots have a fully developed expectation about the incoming sensory signals, which are not matched on the sensory side. (Student pilots on the other hand might more easily suffer from motion sickness when they make their first aerobatic flights: Their expectation too does not match the incoming sensory information.) In flight simulators and in driving simulators, fast maneuvering is one of the provocative factors in inducing simulator sickness. In view of the scheme of Fig. 2, it is obvious that then differences will arise between the vectors \mathbf{v}_{sens} and \mathbf{v}_{subj} , because the simulator cannot stimulate the vestibular system appropriately in those situations due to the limited motion range of the simulator.

Differences between \mathbf{v}_{sens} and \mathbf{v}_{subj} may also arise when there is insufficient temporal concordance between the visual displays and the physical motion of the simulator. Such temporal problems may also add to the motion sickness encountered in virtual reality applications [36].

Clinical Vertigo

The SV-conflict model is also in line with our experience in clinical vertigo: Patients with an acute unilateral deficiency show large discrepancies between the subjective vertical and gravity [8]. Head rotation is therefore rarely about the subjective vertical, causing discrepancies between \mathbf{v}_{sens} and \mathbf{v}_{subj} and therefore nausea. Consequently, they prefer to remain motionless at first to suppress vertigo and nausea. However, compensation is faster accomplished using rehabilitation programs that try to mobilize the patient as quickly as possible, in line with the Kalman filter requirements to learn adequate compensation strategies. It is of interest that those programs often start to make eye movements only, which apparently are disturbing by themselves [31]. Whether this is only due to the spontaneous nystagmus or because eye movements evoke self-motion sensations should be sorted out, also in view of the discussion above about motion sickness and circularvection.

For the clinical vestibular tests that evaluate the motion sickness susceptibility, the SV-conflict theory has consequences as well. More attention should be paid to tests that involve the subjective vertical, especially to those tests that determine the sensory weight factors. Inappropriate weighting of the sensory information correlates to increased motion sickness susceptibility, as shown for instance by Bles et al. [9] and by Harm et al. [24].

who found increased weighting of the visual information in sufferers from sea sickness- and motion sickness-susceptible astronauts, respectively. For motion sickness desensitization courses, training with Coriolis effects with full view of the visual surround should be less effective according to the SV-conflict theory in view of the absence of a conflict between v_{sens} and v_{subj} . It would only have a psychological effect in that it demonstrates the subject that motion sickness will not always follow on head movements during rotation.

DISCUSSION AND CONCLUSION

We propose a theory on motion sickness that is built around the determination of the internal representation of the vertical, (i.e., the subjective vertical). This so-called SV-conflict theory can be seen as a simplification of the classic sensory rearrangement theory, in which motion sickness is attributed to the presence of sensory conflicts. According to the SV-conflict theory, however, there is only one conflict of interest: that between the subjective (or expected) vertical and the sensed vertical. The advantage of having only one underlying conflict is that stimuli no longer need to be classified into different types of conflicts, such as is the case with the sensory rearrangement theory. In the short review of well-known provocative stimuli, we did not encounter major problems in upholding the SV-conflict theory. Despite the often qualitative description, the examples showed that the theory fits the experimental data quite well, in our opinion better than the classic sensory rearrangement theory.

The SV-conflict theory was mathematically implemented as an extension of the model of Oman [33] by adding modules for the calculation of the sensed and subjective vertical and the conflict vector between these two. We believe that the SV-conflict model is straightforward in analyzing whether situations are provocative in terms of motion sickness or not. There is no need for applying different weight factors for different situations to explain why people get sick in one and not in the other condition. Moreover, with respect to the descriptive motion sickness incidence models [19,30], the SV-conflict model does not require special filtering of input signals or the restriction to pure vertical motion.

One uncertainty in the model is how exactly the feedback is organized by which the subjective vertical is updated by the sensed vertical. This requires further research and should also address questions regarding adaptation and habituation. We assume that for habituation to a motion environment, apart from the vector c and the gain K_c in the Oman model, the vector d and the gain K_d are important as well. For instance, suppose a person is habituated to a particular pattern of ship motion. When this person changes orientation aboard the ship (e.g., from upright to supine or from facing bow to facing starboard), the stimulation of sensory systems will change as well. In terms of sensory stimulation then, a quite complex habituation process of the multidimensional vector c would be required. Still, it is common experience that changing one's orientation aboard a ship does not cause motion sickness to pop up again. In our opinion, this could be accounted for by assuming habituation of the subjective vertical, which does not depend on the body orientation aboard the ship.² Moreover, this can be a much simpler process because it only concerns the three-dimensional vector d . People habituated to a specific ship motion pattern may get sick again and require a new habituation process when the motion pattern of the ship changes due to a

transition, for instance, from the North Sea wave patterns to those of the Atlantic Ocean.

It is an interesting question why the subjective vertical is so important that problems in determining the subjective vertical cause motion sickness. One could argue that the vertical is critical for the organism to maintain the upright postural position. This is supported by the view of some workers in this field who have built an entire motion sickness theory around the control of body orientation [37]. Another possible explanation could be the finding that the cardiovascular system needs information to keep the cardiac output adequate for each body position [43].

In conclusion, the assumption that all motion sickness-provoking conflicts can be pinned down to only one conflict is justified in view of the analysis of the different types of motion sickness. It has been demonstrated that most of the experimental data on motion sickness can be explained sufficiently by the SV-conflict model. It is also clear that some experiments in the literature (like the different types of optokinetic stimulus apparatus) should be analyzed in more detail to solve the apparent discrepancies in motion sickness data.

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² Although it is known that the determination of the subjective vertical may be less accurate in a tilted body position as compared with the upright position, this variation in accuracy does not depend on the state of habituation. Moreover, these kind of variations will affect v_{subj} and v_{sens} in the same way, so that they have no consequences for vector d .

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