Motion sickness. Part I: development of a model for predicting motion sickness incidence

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Motion sickness. Part I: development of a model for predicting motion sickness incidence

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Abstract: This is the first part of a two-part paper in which a new theoretical approach for predicting motion sickness is shown and experimentally validated.

In the present paper, two models are proposed, both based on sensory conflict theory and in particular on subjective vertical conflict theory. They analyse motion sickness by evaluating the motion sickness incidence index (*MSI*). They allow the analysis of various typologies of vehicles discriminating among the various vehicle configurations, among the positions that the passenger and/or passenger's body can assume. These two models allow to highlight leakage, adaptation and anticipation.

The first model (UNIPG) is a 3D extension of a previous authors' model based only on vestibular *stimuli*.

The second model ($UNIPG_{SeMo}$) introduces the contribution of the visual system to the perception of motion as well as the contribution to the conflict of that among the senses (*inter-sensory conflict*) never yet formalised in motion sickness prediction models.

Keywords: motion sickness; motion sickness incidence; MSI; subjective vertical conflict; inter-modality motion perception; inter-sensory conflict; visual-vestibular interaction.

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1 Introduction

Motion sickness is a complex phenomenon both physiological and psychological which although tied to the perception of motion does not present an evident relationship between motion and the discomfort level. Numerous factors can be connected to motion sickness but the principal ones are accelerations with low frequency content which are perceived by the vestibular (*otholite and semicircular channels*), visual and proprioceptive systems.

This syndrome has appeared, from a historical viewpoint, evolving in step with the development of means of transportation, as these historical references demonstrate: “Navigating on the sea shows how motion causes the body discomfort”, Hippocrates, 400 B.C.; “I continue to suffer so much from sea-sickness, that nothing, not even Geology itself, can make up for the misery and vexation of spirit”, Charles Darwin, on board the Beagle, off the coast of Valparaiso, 10 March 1835; “I’m dying of motion sickness, it won’t make much difference”, private John Robertson, ‘A’ Company – during the landing at Omaha Beach, 6 June 1944; “Eisenhower smelled victory in the air, but to the men of the AEF whose transports and landing craft had left harbor, the smell in the air was vomit”, D-Day, S. Ambrose.

If percentages sea (*sea sickness*) and road transport are the motion conditions which prove most nauseogenic for passengers, even air (*air sickness*) and rail transport cause considerable percentages of discomfort which can be attributed to motion sickness (Forstberg, 1996; Pethybridge, 1982; Dobie and May, 1996). Moreover, although evidence of illness is statistically insignificant, even space exploration has registered this symptomatology (*space sickness*).

It is interesting to note that not only ‘real’ motion provokes this effect; with the increasing use of virtual reality it has been observed that even conditions of simulated motion (di Zio and Lackner, 1992; Kennedy et al., 1993, 1995) (for example inside simulators or in virtual environments) provoke this discomfort (*cyber sickness*) demonstrating how important the visual sense is in the genesis of the symptomatology.

The research activity conducted in this sector by the Machine Design Group of the University of Perugia in recent years (2001–2003) was aimed at the definition and validation of a prediction model for this disturbance which allows the evaluation of the motion sickness incidence (MSI) index (O’Hanlon and McCauley, 1974; Burns, 1984; Lawther and Griffin, 1987; ISO, 1997) (MSI, an index of the percentage of vomiting passengers at the end of a persistent condition of motion of a certain duration) for a generic 3D motion starting from a few variables that can be measured both experimentally and in simulation. The authors have developed a theoretical model (Braccesi et al., 2001) based on sensory conflict theory (Reason and Brand, 1975; Reason, 1978; Irwin, 1881; Claremont, 1931; Oman, 1982, 1990; Benson, 1988) and in particular on subjective vertical conflict theory (Bles et al., 1998; Bos and Bles, 1998) which, besides obtaining the above-mentioned objective, also allows the analysis of various typologies of vehicles (i.e., autovehicles and trains) discriminating among the various configurations of a vehicle [e.g., standard and tilting trains (Braccesi et al., 2001)], among the positions that the passenger can assume [i.e., front or rear of car (Braccesi et al., 2001)], among the positions that the passenger’s body can assume (i.e., erect and supine). Besides the mentioned peculiarities, it is of fundamental importance to emphasise that this approach allows to highlight leakage (i.e., discomfort decreases when the motion stops) and adaptation (i.e., discomfort does not increase with the persistence of conditions of conflict, even if nauseogenic in themselves but constant over time), phenomena which can be found in common experience and in the literature (Forstberg and Kufver, 1999). This model has been shown to be a step ahead of what the current norms [the first model of Lawther and Griffin (1987) accepted by ISO (1997) 2631] propose.

This paper, besides presenting the model in its 3D version [what has been presented to date was a 2D version used in a rail environment (Braccesi et al., 2001)], extends the numerical/experimental validation of the model, making reference to the results of experimental activities present in the literature (O'Hanlon and McCauley, 1974; Burns, 1984; Lawther and Griffin, 1987; Golding and Kerguelen, 1992; Golding and Benson, 1993; Golding and Markey, 1996; Golding et al., 1997).

An innovative contribution of this work, however, is the introduction of the so-called inter-sensory conflict into the prediction model. The contribution of the visual system to the sensation of motion is introduced (inter-modal perception), as is the contribution to the conflict of that among the senses (inter-sensory conflict, Reason and Brand, 1975) also cause of discomfort but never yet formalised in motion sickness prediction models. For this purpose a mathematical model developed by Telban et al. (2000) and Telban and Cardullo (2001) which simulates the interaction between the visual and the vestibular systems within the motion perception process has been translated and introduced into the original model.

In Section 2, after a brief description of the state of the art (Sub-section 2.1), the theoretical base of the proposed approach and the new predicting model (UNIPG), based only on vestibular *stimuli*, is shown (Sub-section 2.2). Moreover, in the paragraph the numerical/experimental validation of the model is illustrated, making reference to the results of experimental activity present in the literature (Sub-section 2.3).

In Section 3 the model ($UNIPG_{SeMo}$) that represents the innovative contribution of this work is shown. In this paragraph the theoretical approach to visual stimuli modelling and its evolution is decrypted. In particular, the mathematical model developed by Telban and Cardullo is shown (Sub-section 3.1). Finally, the proposed model is illustrated (Sub-section 3.2) and validated (Sub-section 3.3).

2 Motion sickness prediction model: vestibular stimuli

2.1 State of the art

There are several factors that can be linked to motion sickness; the main ones are linear and angular acceleration at low frequencies that are perceived by the vestibular system (otholits and semicircular canals), visual and proprioceptoral[1]. The signals are transmitted to the central nervous system (CNS) to be interpreted. All these sensory data are integrated and recorded in the brain where they are continually compared with one another and with the others stored with past experience. This comparison is carried out subconsciously and allows maintaining equilibrium, moving and performing other activities. New data continue to enrich our experience; our central nervous system practically behaves like a retroactive system.

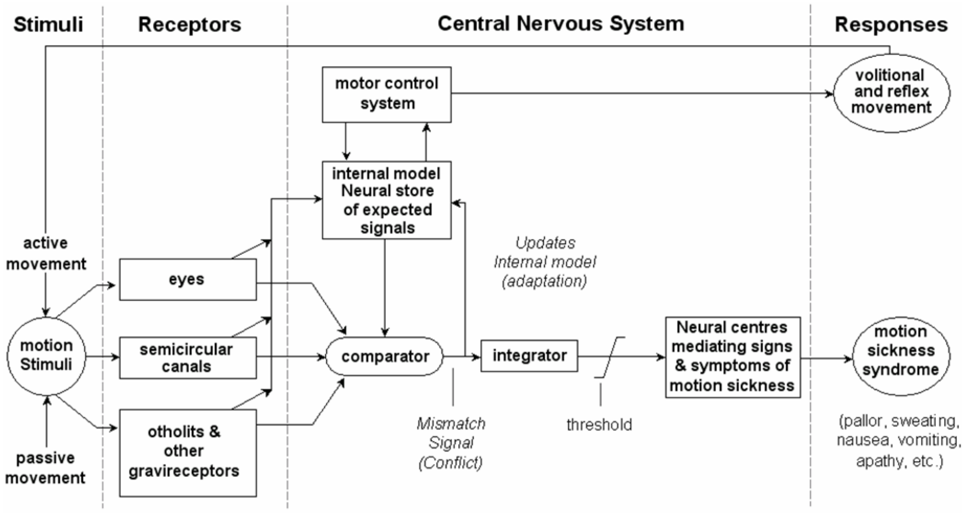
Two different approaches can be used to study motion sickness. The first is the empirical, i.e., it measures the number of people subjected to different kinds of motion experiencing symptoms and then the results are implemented in formulae or models; the only model proposed by the norm to assess motion sickness is an empirical one. The models that belong to the other approach, the theoretical one, attempts to explain why motion sickness occurs.

The empirical approach is certainly the most common and has been used since the first decades of the 20th century even if it has not yielded the expected results so far.

It is restricted to searching the interaction between motion and motion sickness, believing this to be the main cause, while it neglects the other possible causes of stimuli.

As discussed in paper introduction, when using a theoretical approach, the main theory to mention is the 'sensory conflict theory'. The theory is based on work from over a century ago: Irwin (1881) had the idea, Claremont (1931) firstly formalised it and Reason and Brand (1975) and Reason (1978) have rendered it in a modern and mathematical form. Oman (1982, 1990) has developed its final fulfil mathematical description. This theory seems to be the one that better interprets the problem (Figure 1). theory's idea is that all the situations which cause motion sickness are characterised by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, by the vestibular system, and by all the other sensory organs are in disagreement either among one another or among the ones expected based on previous experience. In his theoretical scheme, Reason assumes the existence of a store (neural store) in which the main characteristics are recorded of all sensory data previously received and, the existence of a comparator, which takes from the other sensory organs only information suitably chosen by the memory. According to the author, this difference is the cause of motion sickness.

Figure 1 Sensory conflict theory



Source: Benson (1988)

The key element of Reason's theory is that motion sickness is linked to the difference between the vector that represents all the data perceived by the sensory organs and the vector that represents expected sensory data, which is indeed the sensory conflict.

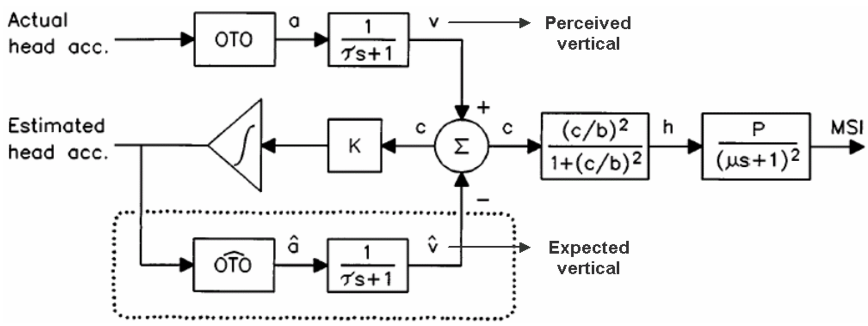
Although many examples of sensory conflict exist which can cause motion sickness, they are, according to Bles et al. (1998) and Bos and Bles (1998) all due to not being able to determine the vertical, i.e., the internal representation of gravity acceleration (*subjective vertical conflict theory*).

In order to prove this hypothesis, the results of some experiments can be reported in which after a long centrifugal motion only the motions of the head which changed with respect to gravity was proven to cause nausea; in a seating position only the roll and yaw motion of the head and not its rotation around a vertical axis would cause nausea, whereas in a laying down position the roll did not have any effect.

It can therefore be concluded that all situations which cause motion sickness are characterised by the condition in which the perceived vertical V_p determined on the basis on information received by the eyes, by the vestibular system and by the proprioceptoral system is in disagreement with subjective vertical (expected vertical) predicted on the bases of previous experience V_a.

Till today Bos and Bles model seems to be the best theoretical model proposed and developed. But the only proposed mathematical formulation is for a simplified model that involves only vertical acceleration (Figure 2). They formulated the general definition but not the general formulation.

Figure 2 Bos and Bles model for vertical motion



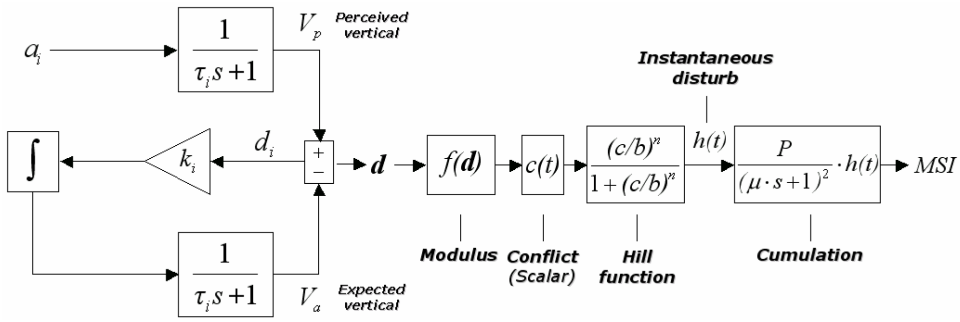
Source: Bos and Bles (1998)

So, in a in a previous work (Braccesi et al., 2001), the authors have translated Bos and Bles theory into a new mathematical model called UNIPG model (2D model) for motion sickness evaluation, presented in a preliminary version, considering the vectorial representation of acceleration field and the vectorial representation of the conflict as defined by Bos and Bles, disregarding sensory data coming from the proprioceptoral system and from the visual system.

2.2 New UNIPG model description

In this paper, first of all, little bit modifications were introduced to the original formulation of the model. The new model is represented for generic input (*i*th linear acceleration) in Figure 3. The input of the model is now a three components vector (3D model), projection of the acceleration felt by the passenger on a reference system fixed on the vehicle, located and oriented as the passenger's head. As in Bos and Bles model, to calculate the perceived vertical V_p, a first order low-pass filter is used to model proprioceptoral system. In general, for each component of acceleration, a filter with different time constants will be needed. These constants are independent of the passengers' head tilt. Moreover, according to Bos and Bles, the estimation of the expected vertical V_a must be performed by coping the transfer functions of the vestibular system adding others functions that can simulate the behaviour of the central nervous system. This choice avoid to have an internal model based on previous experience or a memory store with a mathematical representation of all the situations possible. This task seems to be extremely difficult and tedious. In practice, the conflict *d* multiplied by a factor *k* is used as input to the internal model, composed of an integration and by a low-pass filter similar to the one used to evaluate the perceived vertical V_p. The integrator has been introduced in order to maintain constant the expected vertical when the conflict is zero. Now, the relation between the conflict *d* and the motion sickness index *MSI* can be studied. Since *d* is a tri-dimensional vector it must be firstly changed into a scalar *c* with a suitable function *f*(*d*), e.g., by evaluating its modulus, if the influence of the acceleration direction on the rapidity of nausea onset should be taken into account.

Figure 3 UNIPG model for general input (*i*th linear acceleration)



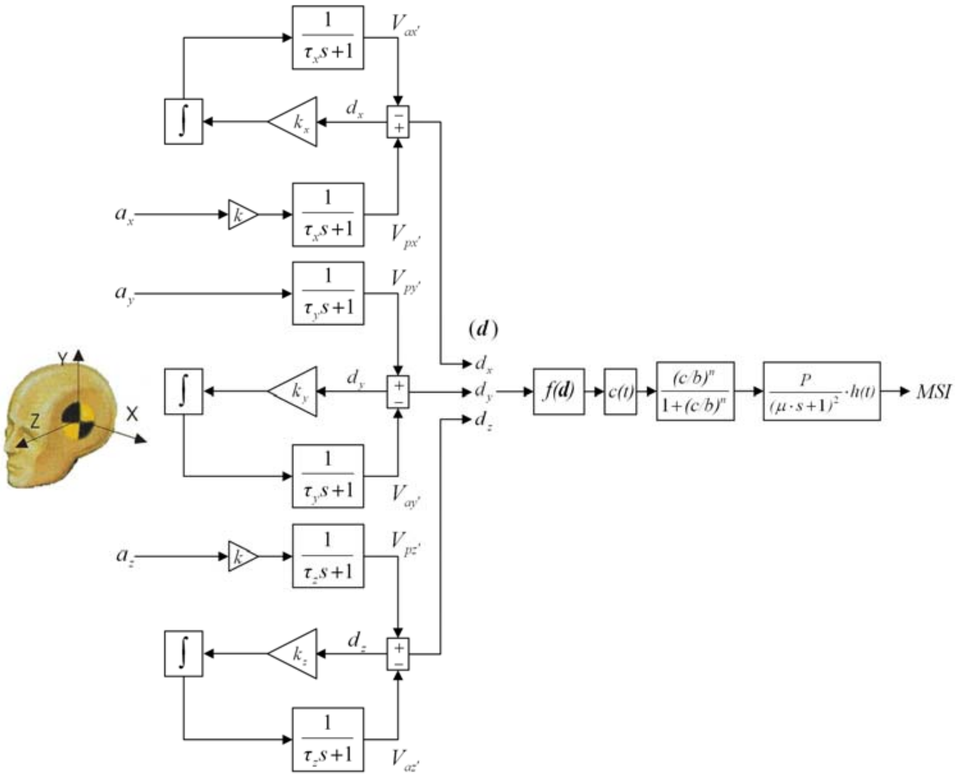
Since the relation between *MSI* and the conflict *d* is non-linear and, the maximum is reached asymptotically, a weighting function with these properties must be used. *Hill function* was chosen also because it has the advantage to fall between 0 and 1 and that it favours high or low values of *d* by suitably imposing parameters *n* and *b*. As a result of the last operation it is possible to obtain the so called *instantaneous disturb*, *h*, index of time domain motion sickness sensation.

The last step is the cumulation of the quantity *h* over time. *MSI* can not exceed 100% and moreover sickness severity returns to zero again after cessation of the conflict. So, in the theoretical model the relation proposed by Oman and Bos and Bles, represented in Figure 3 is used, where *P* explicitly takes into account the maximum percentage of people that perceived sickness.

Starting from the Bos and Bles definition and formalisation, currently still the only one present in the literature, the authors interpreted the philosophy of the *subjective vertical conflict theory* translating it into an evaluation model now formalised for general motion. Inputs to the model are the linear accelerations a_i measured in a reference system fixed to the vehicle, positioned and oriented with the head of the passenger (Figure 4). The outputs available include, besides the MSI index, the value of instantaneous disturb *h*(*t*). It should be emphasised that the availability of an instantaneous index such as the *h*(*t*) index is a feature of theoretical models such as that of Bos and Bles and, therefore, of that presented by the authors. This availability allows one to imagine its use as an ulterior input variable to the generic control system of vehicle motion.

The version of the UNIPG model extended to generic 3D motion, presented for the first time in this work, is represented in Figure 4.

Figure 4 UNIPG model generalised for a 3D motion (see online version for colours)



On analysing the 3D model one can observe that the interpretation of the *theory of subjective vertical conflict* has led to the use of linear accelerations (*otholite*) as the only inputs to the system disregarding gyroscopic accelerations (*semicircular channels*). The implicit hypothesis that the latter cannot in any way influence the perception of the vertical or in any case the condition of discomfort is indirectly confirmed from a theoretical viewpoint by what has been affirmed by Bos and Bles in their two basics works on the above mentioned theory (Bles et al., 1998; Bos and Bles, 1998) according to which gyroscopic accelerations are useful exclusively for projecting, moment by moment, the linear accelerations into an absolute reference system so as to be able to univocally define the characteristics of the filters (direction x, y and z) typical of the vestibular system (Figure 4 and Table 1) through which to filter the results of the projection. This need does not subsist if, as hypothesised, the linear accelerations are evaluated in a reference system fixed to the vehicle, positioned and oriented with the head of the passenger (Figure 4) and therefore with the *otholite*. The results of experimental research conducted by Bos and Bles themselves, having as its object purely gyroscopic motions, have demonstrated that these are not in themselves nauseogenic (de Graaf et al., 1998); this confirms previous affirmations.

Table 1 Parameters of the UNIPG model compared with those of Bles et al. (1998) for vertical motion

Model	τ_y	τ_x, τ_z	k_y	k_x, k_z	*n*	*b*	μ	*P*	*k*
	(s)	*(s)*	(s^{-1})	(s^{-1})	-	-	*(s)*	*(%)*	-
Bos and Bles	5	-	5	-	2	0.7	720	85	-
UNIPG	2.4	0.6	3.36	0.84	2	0.7	900	85	1.414

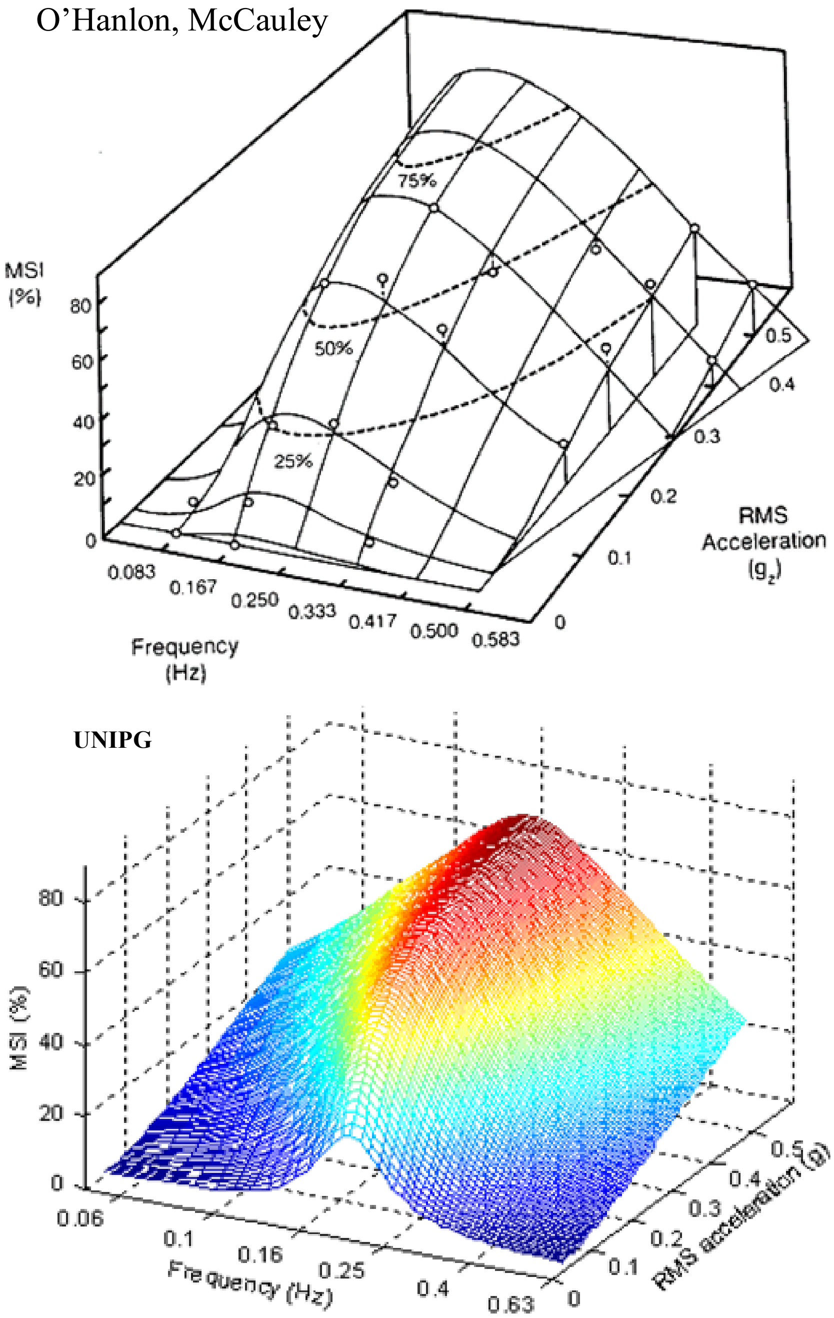
The further decision to treat the two horizontal motions in the same way (Figure 4 and Table 1) derives both from physiological considerations and from the analysis of a series of experiments conducted by Golding and Kerguelen (1992), Golding and Benson (1993), Golding and Markey (1996), Golding et al. (1997) and Griffin and Mills (2002a, 2002b) aimed at analysing the relationship between these motions and sickness. From a physiological viewpoint it is well known that the organ of *otholite* which perceives motion on the lateral plane is the same one that perceives motion on the longitudinal plane (*utricle*). Therefore, since it was necessary to define a mathematical representation for the two sensors, the same one was adopted for both. Experimentally, the cited experimental tests confirm this hypothesis, verifying that the illness indicators found on subjecting persons to lateral and longitudinal motions are comparable.

The parameters that can be found in the model (Table 1) therefore are nothing but the representative constants of the behaviour of the vestibular system (*otholite*). These constants, which differ according to the three directions *x* lateral, *y* vertical, *z* longitudinal have been in part determined using the values already obtained in laboratory tests by researchers who work on the dynamic characterisation of the sensorial system and on the theoretical modelling of motion sickness (Bles et al., 1998; Bos and Bles, 1998) (vertical direction *y*); these were then further refined by the authors in order to better represent the results in terms of MSI obtained by O'Hanlon and McCauley (1974) and Burns (1984). For the other directions (lateral direction *x* and longitudinal *z*) the constants were defined starting always from the activity of characterisation of the vestibular system and, contextually of motion sickness, conducted this time by Golding and Kerguelen (1992), Golding and Benson (1993), Golding and Markey (1996), and Golding et al. (1997). These parameters, once determined, should be considered constants, given the assumption that they represent the dynamic behaviour of the vestibular system of the generic passenger, without being functions of the particular conditions of motion.

2.3 Model validation

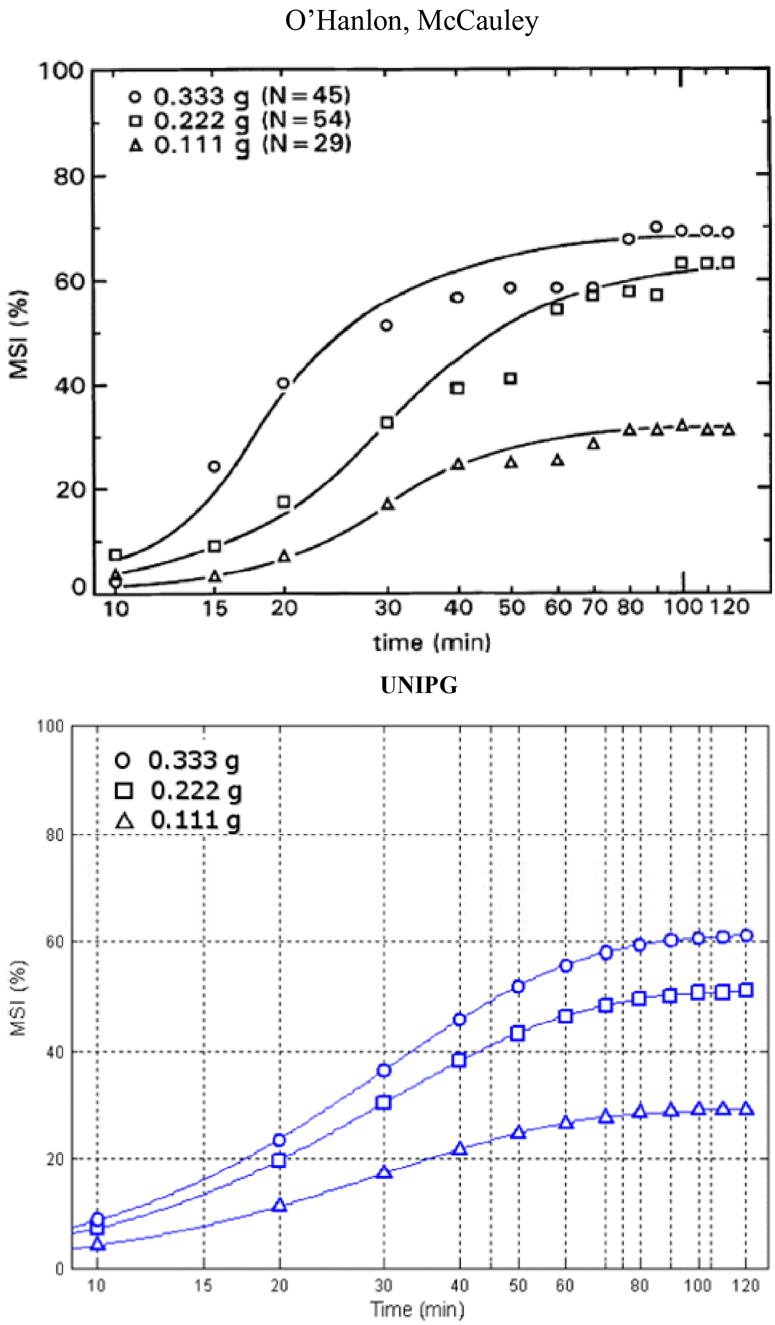
The validity of the model was tested by experimental numerical comparisons using the laboratory activity conducted by O'Hanlon and McCauley as reference for vertical motions (O'Hanlon and McCauley, 1974; Bos and Bles, 1998) (Figures 5–7) and that conducted by Golding and Kerguelen (1992), Golding and Benson (1993), Golding and Markey (1996), and Golding et al. (1997) for horizontal motions. Figures 5, 6 and 7 represent just an example of the experimental numerical comparisons conducted on vertical motions (*y*), all attesting to the validity of the model used not only in terms of the absolute values of the MSI index (Figure 5) but also in terms of its trends in function of frequency (Figure 5) and of motion amplitude (Figures 5–7) and in function of time (Figure 6).

Figure 5 Comparison between MSI maps obtained for sinusoidal vertical motion (see online version for colours)



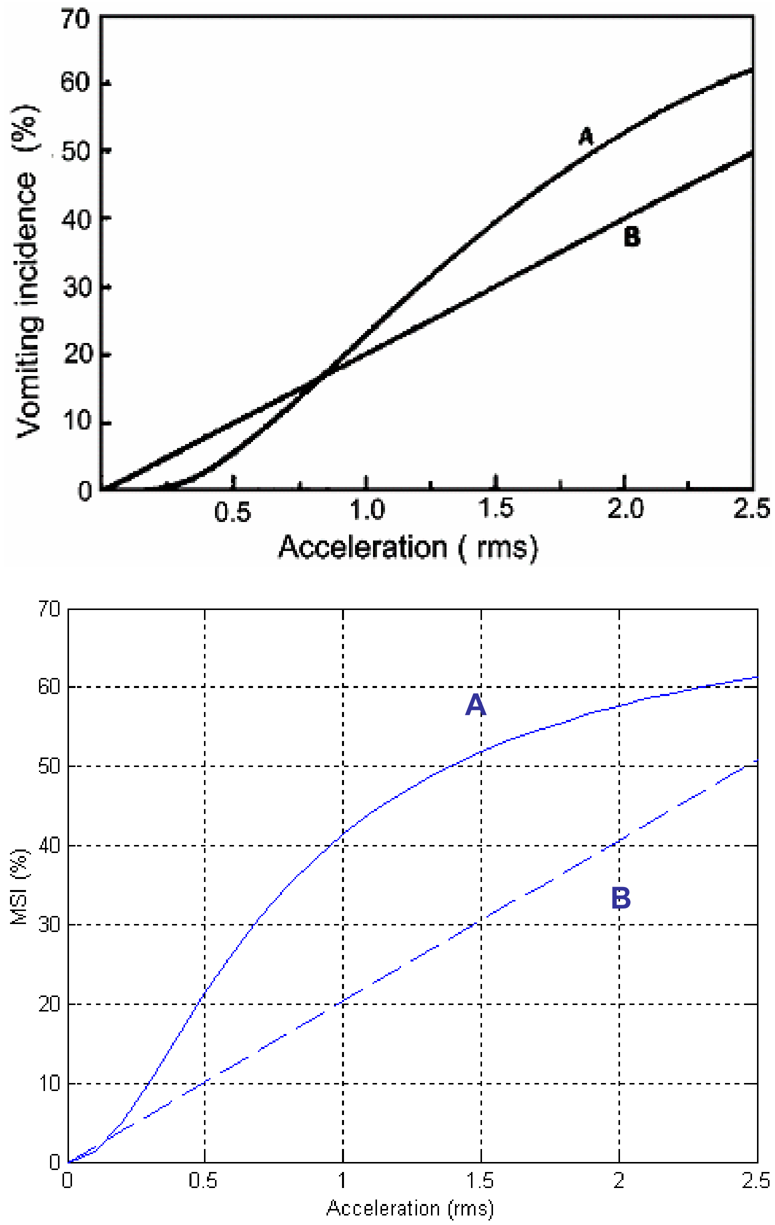
Source: Experimental results obtained by O'Hanlon and McCauley (1974) and numerical ones obtained using the UNIPG model

Figure 6 Numerical experimental comparison between the trends of the MSI index evaluated for an exposition of 2 h to a vertical sinusoidal motion characterised by a frequency of 0.25 Hz and by three different acceleration values (g) expressed in terms of rms (see online version for colours)



Source: Experimental results by O'Hanlon and McCauley [drawn from Bos and Bles (1998)] and numerical ones from the UNIPG model

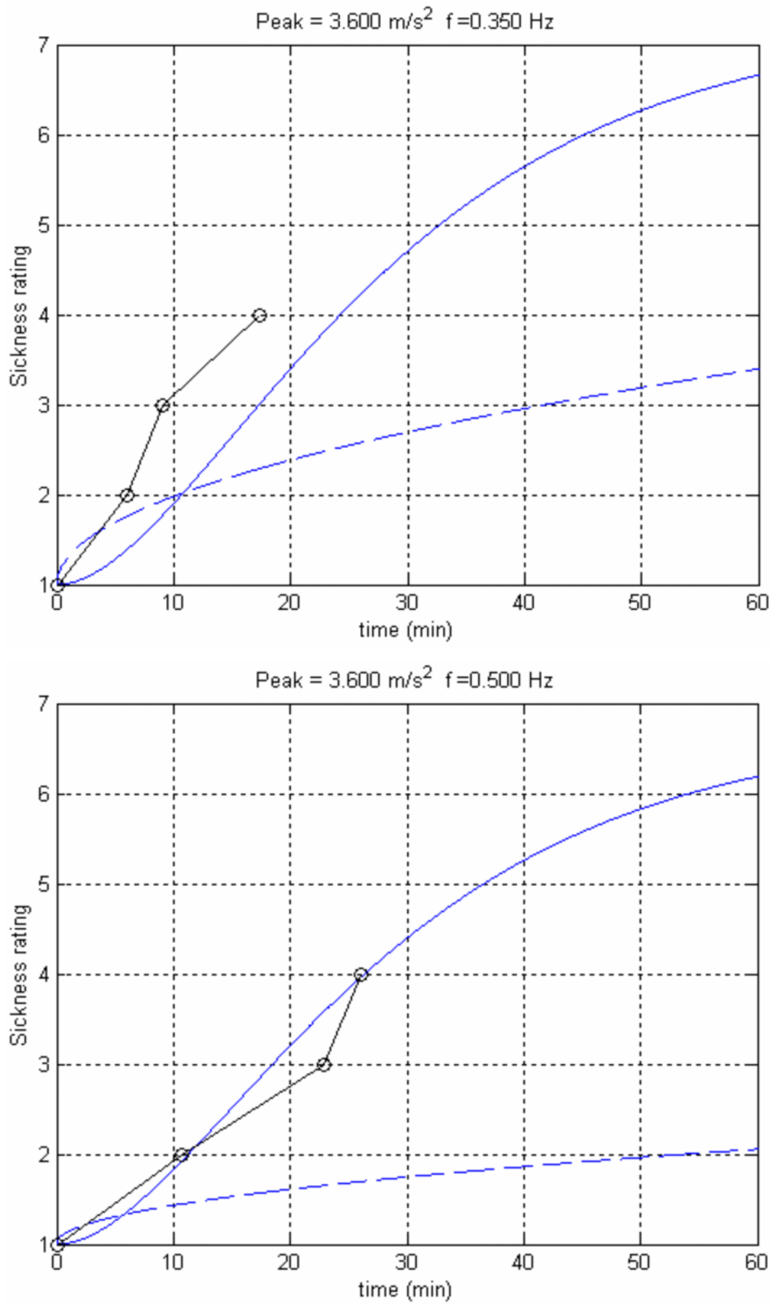
Figure 7 Experimental numerical comparison between the trends of the MSI index evaluated for an exposition of 1 h to a vertical sinusoidal motion characterised by a frequency of 0.2 Hz and function of acceleration amplitude expressed in terms of rms (see online version for colours)



(a) (b)

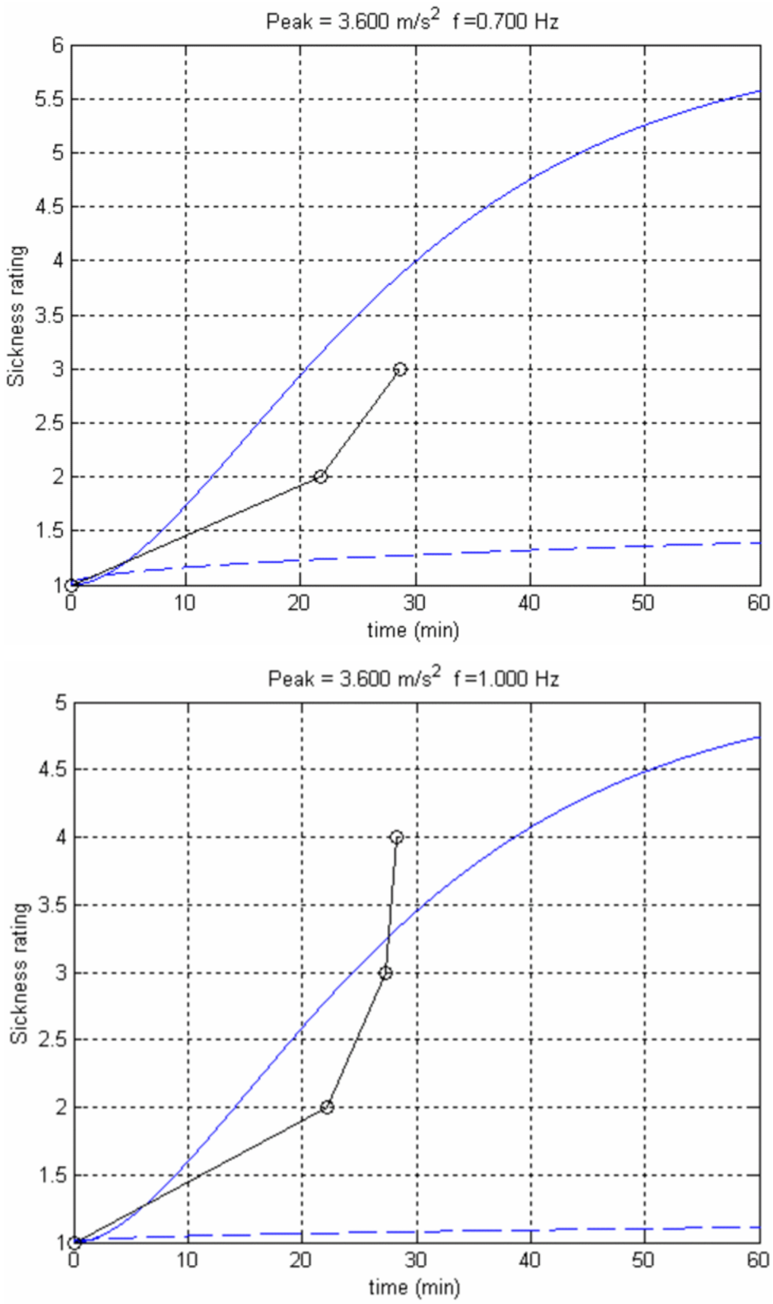
Source: The experimental results were obtained by O'Hanlon and McCauley [(a) line A, drawn from Lawther and Griffin (1987)]. Numerical results were obtained using the UNIPG model [(b) line A] and Griffin's model (line B)

Figure 8 Numerical experimental comparison between the sickness rating trend evaluated for an exposition of 1 h to a horizontal sinusoidal motion characterised by frequency values of 0.35, 0.50, 0.70 and 1.00 Hz and maintaining the same amplitude of 3.6 m/s^2 (see online version for colours)



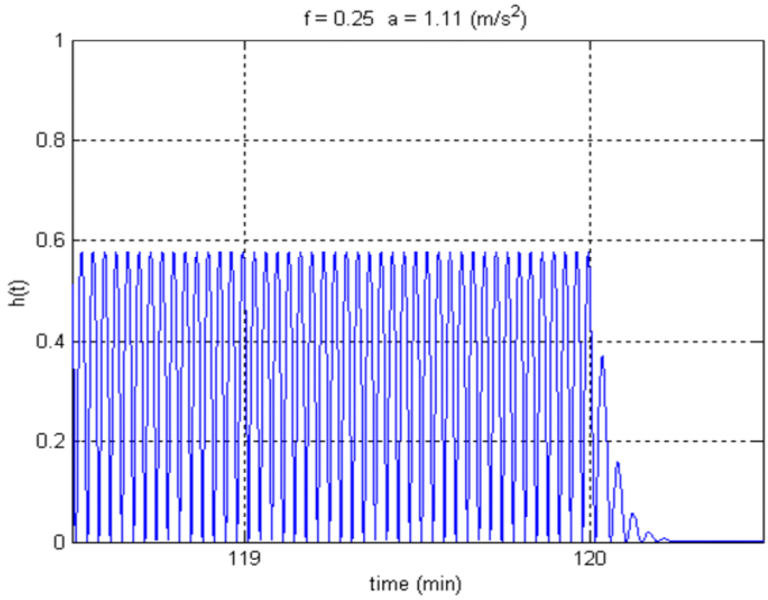
Source: The experimental results were obtained by Golding et al. (1997) (broken curves). The numerical results were obtained using the UNIPG model (continuous curves) and with Griffin's model (dotted lines)

Figure 8 Numerical experimental comparison between the sickness rating trend evaluated for an exposition of 1 h to a horizontal sinusoidal motion characterised by frequency values of 0.35, 0.50, 0.70 and 1.00 Hz and maintaining the same amplitude of 3.6 m/s^2 (continued) (see online version for colours)

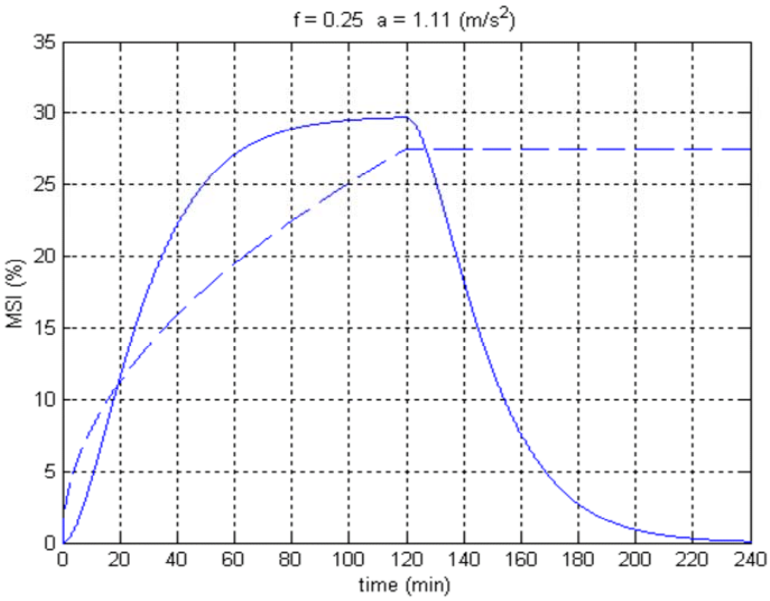


Source: The experimental results were obtained by Golding et al. (1997) (broken curves). The numerical results were obtained using the UNIPG model (continuous curves) and with Griffin's model (dotted lines)

Figure 9 Example of the results that can be obtained with the model developed (see online version for colours)



(a)



(b)

Notes: They represent the trends of $h(t)$ and MSI for a 2 hr exposition to a sinusoidal vertical motion characterised by a frequency of 0.25 Hz and by an acceleration value expressed in terms of rms equal to 1.11 m/s^2. Two hours of absence of motion follow at the end of the exposition. In Figure 9a, the prediction of sickness produced by Griffin's model (Lawther and Griffin, 1987; ISO, 1997) (dotted line) and by the UNIPG model (solid line) are compared.

As far as the horizontal motions are concerned, Figure 8 shows an example of the numerical experimental comparison based on the experiences of Golding et al. (1997), conducted in 1997 on longitudinal horizontal motions. It is important to note that Golding uses as his evaluation index not the usual MSI but an index of sickness called sickness rating or SR defined by him and for which he himself suggests the method of conversion into the MSI index (Golding et al., 1997). From an analysis of the results it can be seen that the UNIPG model (continuous curve) provides results (translated into SR using the abovementioned conversion) in conformity with those gathered experimentally (broken line). On the contrary, Griffin's model of the ISO 2631 standard (broken curve) clearly underestimates the experimental data. The compared analysis of the results illustrated in Figures 6, 7 and 8 demonstrates, moreover, that the UNIPG model, unlike the principal evaluation model existing in international standards, also gathers the trend of the index over time, both for vertical and horizontal motions.

It should be specified that for horizontal motions, as far as the absolute value of the evaluation that can be obtained from the model of the ISO 2631 is concerned, the model proposed by the standard was applied in its original version defined for only the vertical accelerations without introducing the corrective factor k (Table 1) adopted in the model developed by the authors and suggested by Golding and Kerguelen (1992), Golding and Benson (1993), Golding and Markey (1996), and Golding et al. (1997) for horizontal accelerations.

Finally, in order to analyse the ability of this approach to highlight the leakage (e.g., the sickness decreases when the motion stops) and adaptation (e.g., the sickness decreases with the persistence of conflict conditions which in themselves cause sickness but which remain constant in time) phenomena which one encounters in common experience and in the literature, reference motions were simulated and some significant results are reported which demonstrate the ability of the model developed to control these phenomena. If you observe the results indicated in Figures 6, 7 and 9 you will note that in the presence of persistent motion conditions the model predicts a saturation of sickness, that is, an adaptation that the model of Griffin, which by definition obtains a cumulative index (Lawther and Griffin, 1987; ISO, 1997), does not register. It is even more interesting to note how in the case of interruption of the motion and, therefore, of conflict, the theoretical model predicts, in conformity with the experimental data present in the literature (Forstberg and Kufver, 1999), a decrease in the sickness trend which instead is not caught by the standard model as can be predicted from its definition (Figure 9).

3 Motion sickness prediction model: visual-vestibular stimuli

3.1 Visual stimuli modelling

An innovative contribution of this work is the introduction into the prediction model of the so-called *inter-sensory conflict*. While the model developed to this point by the authors and those proposed by the scientific community (Braccesi et al., 2001; Bles et al., 1998; Bos and Bles, 1998) provide for the modelling of the conflict between the senses and the central nervous system (*sensory rearrangement*, Reason and Brand, 1975) considering for the senses only the vestibular system, with this work the contribution of the visual system to the perception of motion is introduced as well as the contribution to the conflict of that among the senses (*inter-sensory conflict*, Reason and Brand, 1975) also at the root of motion sickness but never yet formalised into motion sickness prediction models. To this end, a mathematical model developed by Telban et al. (2000) and Telban and Cardullo (2001) which simulates the interaction between the visual and the vestibular systems within the motion perception process has been adapted and introduced into the original model.

The experimental activity developed in recent decades by the international scientific community to support the evaluation of the capacity of visual stimuli to provoke sickness has been characterised by two principal topics: the comparison between visual and vestibular stimuli (that is, experiments aimed at establishing which of the two is more nauseogenic) and visual-vestibular interaction (that is, experiments aimed at determining a model of the interaction between the visual and the vestibular systems within the motion perception process).

Regarding the comparison between visual and vestibular stimuli, the most significant experiences are reported below. Dauton and Fox (1985) analysed the contribution to *motion sickness* of both sensorial systems (visual and vestibular) reaching the conclusion that visual stimuli alone are the most provocative at low velocities and vestibular ones alone (for example motion of the head or of the whole body) at high velocities. Moreover, the two researchers affirm that visual and vestibular stimuli combined and in conflict (for example one stimulus that indicates motion and the other that does not) are more provocative (that is the symptoms present themselves sooner and are stronger) than if considered separately or than if combined and complementary (for example both indicating motion). Lackner and Graybiel (1985) have investigated the effects of the direction of head motion (for example, rolling and pitching) and demonstrated that all the motions increase susceptibility to *motion sickness*. An important result common to those obtained by other researchers is that the open-eye condition (that is, generally in the presence of stimuli in conflict) is worse (more nauseogenic) than that with closed eyes; the acceleration and frequency of the motion emerge as important factors. di Zio and Lackner (1992), in a joint study, reached the conclusion that both exposition to environments of virtual reality and real motion provoke sensations of sickness. An important result is that the combination of visual stimuli with vestibular ones, even more so in conflict with each other, produces even worse effects. The experiments were conducted using a simulator of vertical motion and a display installed in front of the eyes of the subject being tested able to register and retransmit images of the motion with an assigned delay. Finally, Parker and other researchers from the University of Washington (Parker et al., 2001) reconstructed the frequency response function of the visual motion perception system. The conclusion they reached was that sickness is provoked by conflict between visual and vestibular signals, but also that conflict is greatest in the frequency interval in which both the visual and the vestibular systems are active and not necessarily more sensitive to the motion. In fact, the subjects reported more severe symptoms for motions at lower frequencies than those usually registered in conditions of exclusively vestibular stimuli (approx. 0.15 ÷ 0.20 Hz) and in syntony with the frequency behaviour of the visual system characterised by a maximum at very low frequency indicating a region of maximum sensitivity between 0.01 and 0.1 Hz.

The conclusion that can be drawn from this heterogeneous series of experiments and studies is that visual stimulus is significant only at low oscillation frequencies and, that is, that the visual motion perception system presents the characteristics of a low pass filter. Moreover, considering the response of the vestibular system one can affirm from the experimental outcomes that the conflict component due to visual-vestibular interaction, reaches a maximum of around 0.05 Hz.

As far as experimental activity on visual-vestibular interaction is concerned, instead, the experiences conducted by Zacharias and by Young should be noted. Zacharias (1977) documented, though studies of neurophysiology, that the visual and vestibular stimuli are closely interconnected within the motion perception process. Moreover, he quoted a study of Young and others, in which the subjective velocity (perceived by the subject) was measured as a response to a combined rotation (both of the subject and of the image) around the vertical axis. The study demonstrated that the subjective velocity was strongly influenced by *vection* (visually induced sensation of motion) but did not correspond to the simple sum of the vestibular perception and of the illusion of motion. Young (1978) noted that in conditions of no motion visual stimulus dominates the perception of velocity up to a frequency of 0.1 Hz. At higher frequencies the vestibular stimulus prevails. He suggested that when both stimuli were present, these should be combined according to a non-linear law, preferring visual input for congruent stimuli and vestibular input for stimuli in conflict.

While the motion sickness prediction model developed at this phase by the authors (Braccesi et al., 2001) and those proposed by the scientific community (Bles et al., 1998; Bos and Bles, 1998) provide for the modelling of conflict between the senses and the central nervous system (*sensory rearrangement*, Reason and Brand, 1975) considering for the senses just the vestibular system, to date no motion sickness prediction models which introduce the contribution of the visual system to the sensation of motion or that to conflict coming from the conflict among the senses are noted in literature. On the other hand, there have been many attempts to define motion perception models that take into account both vestibular and visual input. Their importance lies in the fact that the sensation of motion perceived by the subject is the result of a combination of visual and vestibular stimuli. The authors therefore have attempted to introduce into the original UNIPG model a functional block that would simulate the interaction between the visual system and the vestibular one within the motion perception process.

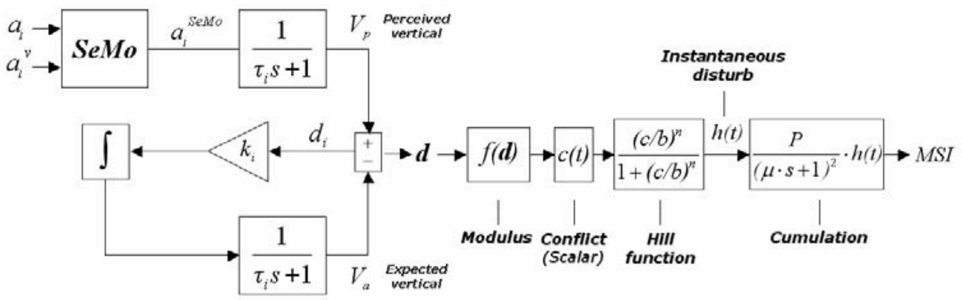
The most important perception models present in the literature are quoted below. Zacharias (1977) developed a perception model for motion around the vertical. For low conflict values, for example when inputs agree, the sensation of motion is calculated through a weighted sum of the two signals. For high conflict values, the weight of the visual stimulus is reduced and that of the vestibular stimulus is increased until the conflict decreases. Borah et al. (1988), subsequently, developed a model of visual-vestibular interaction, which included the implementation of an estimator, a sort of central processor of sensorial input that included a modified version of the model of Zacharias. van der Steen (1988) proposed a motion perception model in which the vestibular and visual stimuli were combined to obtain the sensation sensed by the subject. Unlike in the model proposed by Zacharias, an evaluation of conflict was not made. van der Steen introduced the concept of a neural filter within the model. The neural filter transfers the response of both the senses (visual and vestibular) to a physical variable. The transfer function, below the filter, represents the estimator of the motion. The signal coming out of the model is the sum of the optokinetic influence and of the vestibular perception.

The work that emerged as the most interesting, however, both from a viewpoint of mathematical rigour and of compatibility with the model developed to this point by the authors, is the integrated visual-vestibular model of Telban et al. (2000) and Telban and Cardullo (2001). It should be noted that the activity of Telban and Cardullo is not part of research activity on motion sickness prediction but forms part of activity aimed at the comprehension of the perception of motion in the aeronautic and aerospace areas. The objective of the two researchers was to develop a motion perception model that included both visual and vestibular stimuli. The model also evaluates the effects of a visually-induced sensation of motion, the so-called *vection*. Telban and Cardullo first reviewed all the already existing models on visual-vestibular interaction, affirming that a simple linear sum of the two stimuli was not able to reproduce the perceived response and suggesting that each stimulus should be weighted on the basis of their conflict. Moreover, they formulated the hypothesis that the visual evaluation of motion is an optokinetic influence that is formed by filtering the difference between the stimuli through a low pass filter. In their works (Telban et al., 2000; Telban and Cardullo, 2001), both a rotational model (angular velocity) and a translational one (linear velocity) were proposed. Both incorporate the mathematical models of the vestibular dynamic (*semicircular channel* for the former, *otholite* for the latter) and a conflict estimator that controls the level of the optokinetic influence (this estimator also permits the modelling of *vection* latency). As suggested by Borah, the visual stimuli of motion are by hypothesis limited to peripheral scenarios such as that supplied by a flight simulator with a vision broad field. An example of peripheral scenario might be the passage of stars or clouds within the field of vision. Not all the details present in the structure of the scene, therefore, are considered.

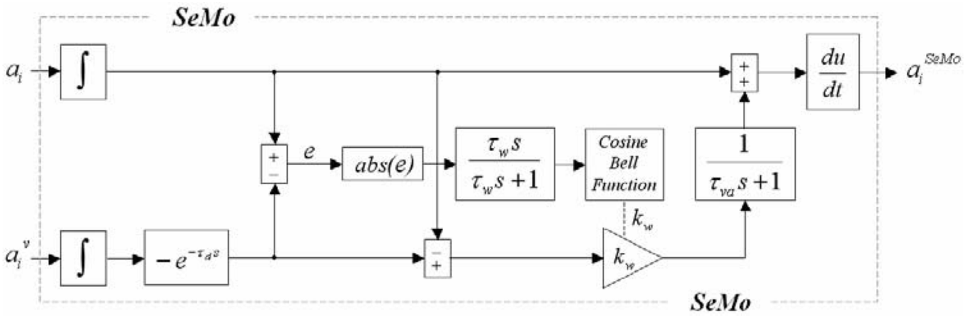
3.2 UNIPG$_{SeMo}$ model description

Therefore, in order to introduce the effect of visual stimulation as a correction of the perception of motion into the motion sickness prediction model developed by the authors (UNIPG), up to now exclusively guided by the vestibular system, the model of Telban and Cardullo has been interpreted and translated within the UNIPG model. Consistent with the philosophy adopted and, that is, consistent with the theory of subjective vertical conflict only the translational model has been considered: only the linear components of the motion are analysed. The model of Telban and Cardullo has a rather simple dynamic and recuperates some components already proposed by the results listed previously and obtained by the other researchers. Input of the original model are the specific force that stimulates the *otholite* and the visual acceleration a_i^v. As output of the model we obtain the linear velocity perceived by the subject as an effect of the combined visual-vestibular stimulation. Both the inputs pass through the respective transfer functions (vestibular and visual) originating the two sensorial perceptions. As proposed by Zacharias, the visual signal passes through an internal model of the vestibular dynamic (*otholite* transfer function), so as to produce the expected vestibular signal which will then be subtracted from the perceived vestibular signal. The absolute value of this difference *e* (*rectified error*) passes through an adaptation operator, generating a signal of conflict v_{err} (*washout error*). This operator determines how long a constant state of conflict between the signals can persist. Zacharias suggested to choose the adaptation constant τ_w on the basis of the latencies observed in the simulators. For linear velocity a value of 1 s was assigned to the adaptation constant τ_w to generate the latencies already obtained in the previous studies. Beginning with v_{err} the value of k_w (the weight of the optokinetic influence) is calculated by means of the modified cosine Bell function suggested by Borah. The value of k_w varies from 0 to 1. A high conflict value, greater than an assigned threshold value ε, brings k_w to zero. While a value below the threshold, brings k_w to a value between 0 and 1, reaching the unit when v_{err} goes to 0. For v_{err} less than 0, k_w remains equal to 1. The threshold value ε was chosen equal to the minimum speed value that the *otholite* can perceive. Zacharias estimated a threshold of 0.2 m/s after some experiments conducted by Meiry in a simulator for linear motion. Finally, even in this model the optokinetic influence proposed by van der Steen is introduced. The time constant τ_{va} is assumed to be equal to 1 s, a characteristic of the low pass filter proposed by Young.

Figure 10 (a) Representation of the model developed ($UNIPG_{SeMo}$) and (b) of the functional block SeMo



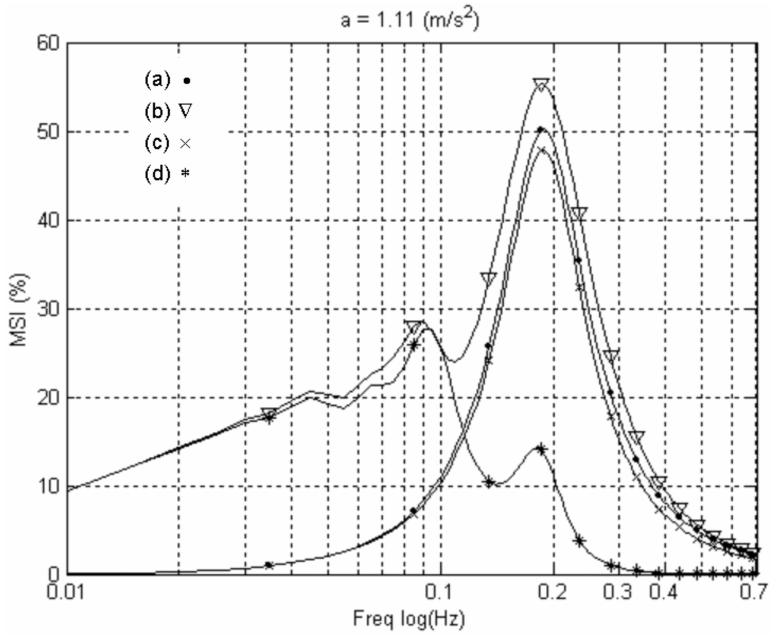
(a)



(b)

The following modifications have been made to the description corresponding to the original version of the model of Telban and Cardullo. In Figure 10, the perception model Sensory Model (SeMo) developed by the authors is represented. The model respects the original definition of Telban and Cardullo faithfully enough. The first modification was made to the inputs to the vestibular system; rather than the specific force that stimulates the *otholite* the absolute linear acceleration a_i is used. In order to make this model compatible with the motion sickness prediction model the output, originally defined in terms of perceived velocity, is derived with respect to time obtaining the perceived linear acceleration a_i^{SeMo}. Finally, it should be noted that the transfer function of the vestibular system, in congruence to the hypothesis adopted to date (model of Bos and Bles and UNIPG model) has been considered unitary. As a consequence the formulation of the new motion sickness model was simple. The input to the model are now the absolute linear accelerations a_i measured in a reference system fixed to the vehicle, positioned and oriented with the head of the passenger, and also the accelerations related to the peripheral field of vision a_i^v evaluated in relation to the same reference system. The available outputs are always the MSI index and the value of the instantaneous disturb *h*(*t*). The model developed in this way, $UNIPG_{SeMo}$ (shown in Figure 10), is characterised by the functional block *SeMo* which, in fact, represents an evolution of the model and which lies before the low pass filter used in the evaluation of the perceived vertical V_p starting, this time, from the perceived acceleration a_i^{SeMo}.

Figure 11 Results of the $UNIPG_{SeMo}$ model in various conditions of sensorial stimulation

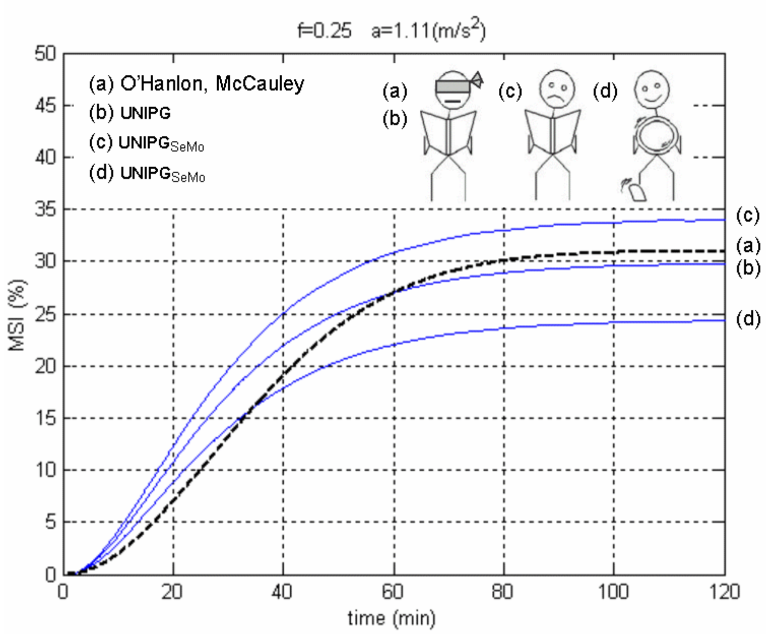


Notes: Exposition of 2 h to a vertical sinusoidal motion characterised by a frequency between 0.01 and 0.7 Hz and by an acceleration value expressed in terms of rms equal to 1.11 m/s^2. (a) Real motion with blindfolded subject, (b) real motion with subject that observes an absence of motion, (c) real motion with subject that sees the motion, (d) virtual motion with motionless subject that sees the peripheral scene in motion.

3.3 Model validation

Then a series of tests were conducted to evaluate the ability of the $UNIPG_{SeMo}$ model to predict the incidence of sickness in the presence of visual-vestibular stimuli in congruence with the experimental results described briefly above. To this end, conditions of real and virtual motion with various combinations of visual and vestibular stimuli were analysed. As an example, in Figure 11, a comparison is made between the MSI values obtained under four different stimulation conditions. All the stimulations were characterised by simple sinusoidal vertical 'motions' with acceleration rms amplitude equal to 1.11 m/s^2 and frequency varying between 0.001 and 0.7 Hz. The duration of the motion was estimated at 2 h. We considered a condition of real motion with blindfolded subject, a condition of real motion with the subject observing an absence of motion (typical of motion conditions in a closed environment), a condition of real motion in which the subject sees the motion (typical of motion conditions in open spaces or in which it is possible to see outside), and finally a condition of virtual motion, that is, the subject is motionless and sees the peripheral scene in motion, typical of conditions of *cyber sickness*. One can observe from the results that the visual sensation, in congruence with what was previously affirmed, prevails over the vestibular sense at low frequencies reaching a maximum effect in a range between 0.08 and 0.12 Hz while, as noted, the vestibular sense is dominant at high frequencies with a maximum of approximately 0.2 Hz.

Figure 12 Example of the results that can be obtained with the model developed (continuous curves) compared with the experimental ones obtained by O'Hanlon and McCauley (1974) (dotted curve) (see online version for colours)

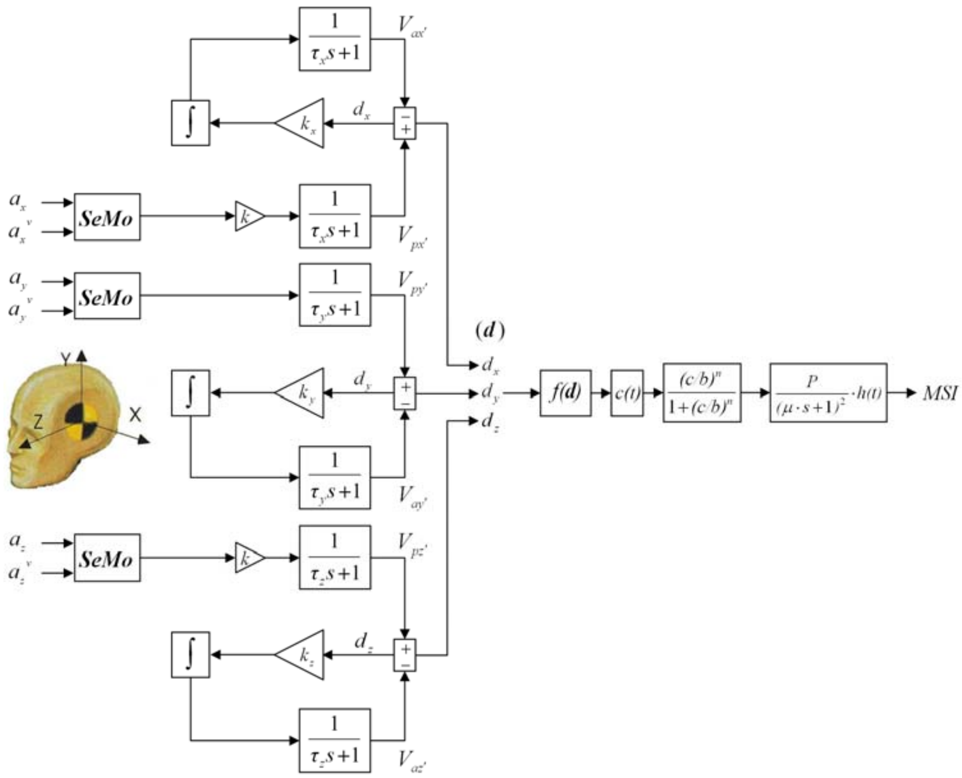


Notes: The trends of MSI for an exposition of 2 h to a vertical sinusoidal motion characterised by a frequency of 0.25 Hz and by an acceleration value expressed in terms of rms equal to 1.11 m/s^2. The experiments of O'Hanlon and McCauley (1974) were conducted on blindfolded volunteers.

It must be highlighted that introducing the contribution of the visual sensorial system allows us to add to the capabilities of the model not only that of predicting the response of the subject even in conditions of virtual motion, but, in particular, of simulating the phenomenon defined as 'anticipation' which is typical of the response to motion of passengers absorbed in reading (visual sensation of motion absent, that is, *high inter-sensory conflict*) and of passengers subject to the same motion but who observe ('anticipate') the motion conditions (visual sensation in agreement with that coming from other sensorial organs and therefore minimal *inter-sensory conflict*). This result can be observed in Figure 11 and particularly in Figure 12, where the classic travel conditions of a generic passenger are compared. It is evident that a vestibular stimulation in conflict with the visual stimulation (condition c in the figure) is more nauseogenic than a stimulation condition with concordant stimuli (condition d). The situation of the absence of visual stimuli (blindfolded subject) is generally intermediate between the two as shown in the example in the figure (conditions a and b).

mA further development of the inter-sensorial model was its extension to generic 3D motion in analogy with the UNIPG model; the same constants were used (Table 1) introducing, therefore, the corrective factor *k* for horizontal accelerations. This coefficient was used (Figure 10) as gain of the perceived horizontal acceleration a_i^{SeMo}. The 3D model version is illustrated in Figure 13.

Figure 13 UNIPG$_{SeMo}$ model generalised for a 3D motion (see online version for colours)



4 Conclusions

In conclusion, it can be affirmed that the model developed is a valid tool for the evaluation of the sickness conditions determined by the vestibular (UNIPG) and visual-vestibular (UNIPG$_{SeMo}$) stimulations associated with generic motions, and has also proven able to fulfil all the purposes proposed. With regard to the UNIPG model, the extensive validation activity conducted, based on the experimental results available in literature, has demonstrated its validity. With regard to the UNIPG$_{SeMo}$ model, this has been shown to be able to discriminate the various situations of visual-vestibular interaction, obtaining results in agreement with common experience (Figures 11 and 12). Future research activities will be aimed at an in-depth activity of theoretical-experimental validation of this model.

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Notes

1 The sensorial information that the nervous system elaborates to maintain balance or for any other motion performance come from the esteroceptoral (sight, sense of hearing and touch, etc.) and from the proprioceptoral system (internal state of the system).