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Appropriate Use of Virtual Environments to Minimise Motion Sickness

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1. Introducton

With the current fast rate of technological developments and the high requirements for training with sophisticated apparatus, the military has become more and more involved in working with simulators. The term "simulator" here means: a systems that has the potential to create sensations of passive or active self movement in a simulated environment. This definition of the term "simulator" not only applies to the traditional flight simulators, both with and without a moving base, but also to Virtual Environments (VE) set-ups implemented in Head Mounted Display (HMD) systems, which no doubt will become part of future flight training programs.

Apart from the obvious usefulness of such simulators, they also have a serious disadvantage: it turns out that they expose users to discomforting and unwanted side-effects, that might well affect training efficiency. One of the most important and well known problems is that these simulators often induce motion sickness, which severely interferes with behaviour and thus with training. Motion sickness causes lowering of motivation, usually resulting in a considerable slowing down of work rate, a disruption of continuous work, or even its complete abandonment. In fact, motion sickness in simulators is currently the main factor limiting the use of simulators.

There are various kinds of motion sickness, such as air sickness, sea sickness, car sickness, space sickness, and some people may even get sick in trains or elevators.
Simulator sickness is basically a form of motion sickness. It has been defined as motion sickness which occurs in a simulator, but which would not occur in the real world in the same circumstances as those which are simulated [28]. For instance, if a person gets sick in an aeroplane and also in a simulator, which validly mimics the flight movements, then this would not classify as simulator sickness. We only speak of simulator sickness if that person would become sick in the simulator but not in the aeroplane. The same reasoning applies to motion sickness in virtual environments.

In order to be able to minimise the incidence of motion sickness in virtual environments, it is necessary to understand the reasons for simulator sickness, and thus for motion sickness in general. Therefore we will briefly review our present view on motion sickness. This will then allow us to understand why some factors are important to lower the motion sickness incidence in virtual environment applications.
Finally we will discuss other, often related, human factor problems that happen frequently in virtual environments, such as headaches, eye strain and after-effects, and mention what might be done to minimise these effects.

2. Motion sickness in general

Motion sickness may vary among subjects: within individuals, there is no direct correlation between sensitivity to various forms of motion sickness. Sensitivity to any particular form of motion sickness also varies largely among humans. Moreover, motion sickness may develop fast or slow. Women are generally somewhat more sensitive than men. There seems to be an effect of age as well. Sensitivity for motion sickness is very low with children a few years old, then increases and at old age decreases again [36].
It is known that, after its initial rise, motion sickness eventually decreases with time despite ongoing motion exposure. This adaptation may take a few hours up to a few days, as with sea or space sickness. But again, the time it takes for the symptoms to disappear differs among individuals. With approximately 5% of humankind adaptation does not take place at all.

All this makes it difficult to understand the nature of the provocative motion stimulus. In a series of experiments, carried out in a Ship Motion Simulator (SMS), McCauley et al. suggested that it is mainly the vertical component of ship motion that causes sea sickness [34]. For sinusoidal vertical motion they found motion sickness to be most prominent between 0.05 to 0.8 Hz (maximum at 0.2 Hz) and with amplitudes of over 1 m/s^2, the incidence of motion sickness increasing further at higher amplitudes. On the basis of their data these authors developed a descriptive mathematical model of sea sickness [31]. More recently another mathematical motion sickness incidence model has been proposed by Griffin, allowing also for complex vertical motion patterns [23] (for comparison of these two models, see [16, 17]). These models became the basis for the international standards. The main premise of these descriptive models is that varying vertical accelerations are an important factor in the generation of motion sickness.

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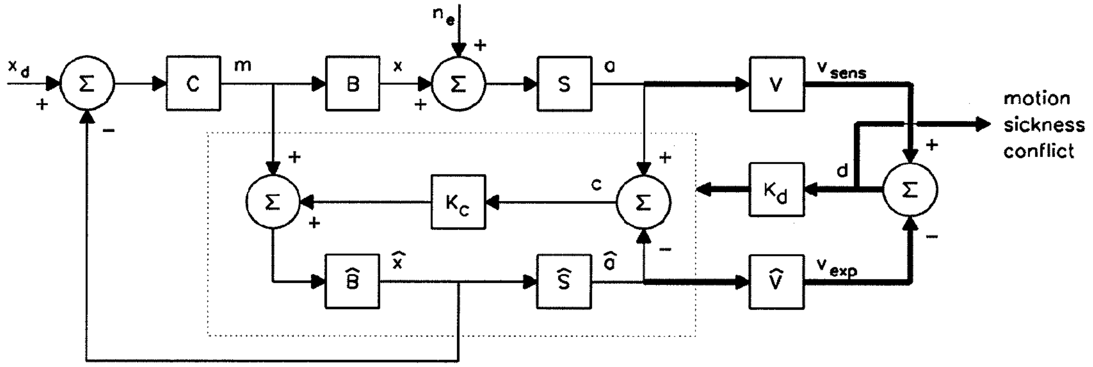

Fig. 1 Instead of the conflict vector **c** from the Oman model [35], the subjective vertical motion sickness model considers the vector **d** to be the conflict vector for generating motion sickness. The modules V are necessary for the computation of the subjective vertical (thick lines). The dotted lines represent the internal model.

It has also been shown that motion sickness may develop as a result of horizontal linear movements [22, 25].
Furthermore, the notion that only vertical movements are sea sickness provoking, has been challenged in a series of experiments by Wertheim with a ship motion simulator [43]. He observed motion sickness even when vertical movements — which, according to the above mentioned mathematical theories, were too weak to generate motion sickness — were accompanied by low frequency pitch and roll motions. Head movements still further increased the motion sickness incidence [42]. Ergonomic measures to counter motion sickness at sea included the design of a working place such that head movements could be minimised [4].
Head movements which changed the orientation of the head with respect to gravity also proved to be very provocative in subjects who had been submitted previously to constant hyper gravity in a human centrifuge (2–3 g for 1.5 hrs [7, 33]).

These examples illustrate the view that the vestibular system plays a crucial role in the generation of motion sickness [21, 36]. In fact, it has long been known that the one necessary requirement for any kind of motion sickness is a functioning vestibular apparatus. People who do not have a functioning vestibular apparatus (because of particular illnesses) simply cannot become motion sick [e.g. 29].
However, vestibular-visual interactions are also very important in provoking or preventing motion sickness: the driver of a car does not get sick, whereas the passenger reading in the back seat may have a fair chance of getting sick on a curved road. Somatosensory-vestibular interactions also prove to be important in the incidence of motion sickness as was demonstrated with (Pseudo-)Coriolis effects [6]. Especially with VE these interactions are very important.

This is not the proper place to present a detailed description of how the vestibular apparatus works. Many good texts on the subject ore available elsewhere (e.g. Guedry [24], or Howard [26]. Here it suffices to note that the central role of the vestibular system is recognised in what are currently the most well known explanatory theories of motion sickness, like the theory of intersensory mismatch [35, 36].
A more specific version of this theory assumes that motion sickness results from only one mismatch, the one between the expected vertical and the vertical as determined on the basis of the incoming sensory information [8]. There are some other alternative theories based on ecological perspectives [39, 44], and there are ideas about cognitive influences on motion sickness [19], but here we will focus primarily on the view that motion sickness arises when there is a mismatch in the determination of the gravity representation.

According to the sensory mismatch theory from Reason and Brand [36], motion sickness occurs when the sensory systems provide the brain with more than one kind of self-motion information which do not match each other. This could be either an intra- or an inter-sensory conflict.
The sensory mismatch theory offers some remedies for motion sickness. For example, in the case of a ship at sea, the incidence and severity of sea sickness under deck should be reduced when the visual system is provided with an optic pattern which remains stable not relative to the eyes, but relative to the real world. This was proposed by Bittner & Guignard [4] and it fits the experience that standing on deck with view of the horizon is less provocative than standing under the deck. In fact there have been some attempts to investigate possible motion sickness reducing effects of an artificial horizon [10, 38].

3. The subjective vertical mismatch concept

Although many examples of conflicts between and within sensory systems can be described, leading to disorientation and motion illusions indeed, there is plenty of evidence that motion sickness is primarily provoked in those situations where the determination of the subjective vertical, the internal representation of gravity, is challenged. Therefore the sensory rearrangement theory on motion sickness was redefined to: “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 non-vestibular proprioceptors is at variance with the subjective vertical as predicted on the basis of previous experience” [8, 9]. In Fig. 1 this concept is illustrated. Since with this model in principle motion sickness incidence can be described for every stimulus condition, such an approach would be more useful than the descriptive models as discussed above for sea sickness, since these descriptive functions only apply to particular stimuli which have to be determined first. We therefore explain this model in more detail for the situation of walking towards a certain position.

In Fig. 1 we see that, in order to obtain 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 **a**. The internal model consists of the same components (indicated with a hat) and computes the expected sensory information $\hat{\mathbf{a}}$. Differences between the vectors **a** and $\hat{\mathbf{a}}$ are calculated, and are fed back into the system. In this way an optimal estimate of the actual walking path can be obtained.

The Subjective Vertical conflict model extends the Oman model [35] with a network V which constructs the sensed vertical, $\mathbf{v}_{sens}$, based on the incoming sensory information. Similarly, in the internal model a network $\hat{V}$ is added which constructs the expected vertical, $\hat{\mathbf{v}}$ or $\mathbf{v}_{exp}$, based on previous experience and expectation. The difference vector **d** between $\mathbf{v}_{sens}$ and $\mathbf{v}_{exp}$ is used to update $\mathbf{v}_{exp}$, and is in our view the conflict vector which generates motion sickness [8] (see Fig. 1).

For analysis of the provocativeness of motion conditions it is of great importance to know how the representation of the vertical is accomplished [8, 11].

This is in fact the basic vestibular problem for the central nervous system. In Fig. 2 it is shown how this could be accomplished on the basis of psycho-physiological evidence. The vestibular (semi-circular canals, SCC, and otoliths, OTO), the visual (VIS) and the somatosensory (SOM) system all provide information on spatial orientation. In order to obtain only one unique spatial orientation it is assumed that all this sensory information is integrated (INT) into basically three signals, indicating the sensed rotation (SR), the sensed translation (ST) and the sensed vertical (SV) as shown in Fig. 2 [8].

The integration of rotatory motion information is rather straightforward, because the sensory systems provide complementary information. A more complex problem for the central vestibular system is to extract the gravity information out of the sensed gravito-inertial force vector. In view of normal human movements and locomotion, it was hypothesised that low-pass filtering (LP) of the signal representing the gravito-inertial force vector could preserve gravity. This is a sensible approach, provided that the angular motion information helps to compensate for the consequences of fast head tilts. Mathematically this compensation is accomplished by a transformation R of the co-ordinate frame with the otolith vectors, over the angle of the head tilt indicated by the rotation sensors. Such a manipulation keeps the input to LP unchanged, the sensed vertical after the head tilt being determined by the rotatory motion information due to the inverse transformation R^{-1} as shown in Fig. 2.

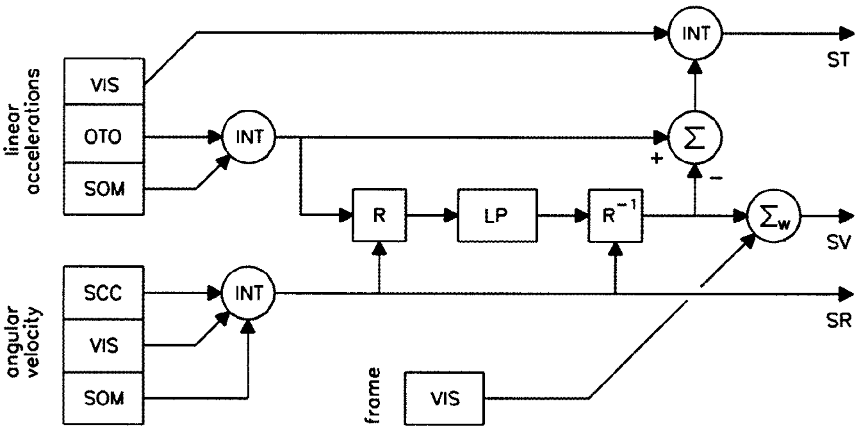

Fig. 2 Integration of sensory information.

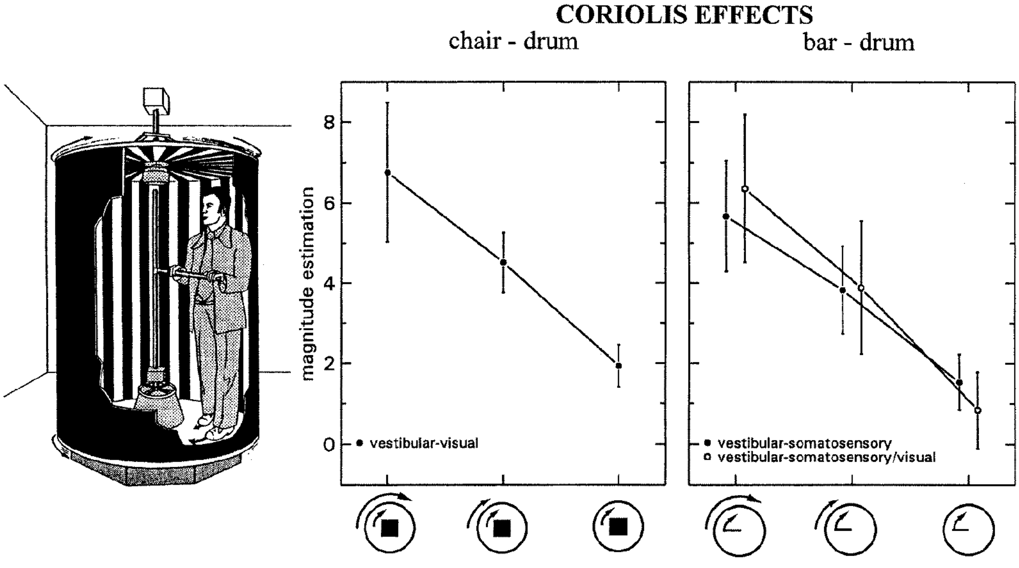

Fig. 3 Differential effects of congruent and incongruent visual and somatosensory motion stimulation on the magnitude of the vestibular Coriolis effect (5 is the standard magnitude of the discomfort of the vestibular Coriolis effect).

It is assumed that the internal model uses a similar neural network as on the sensory side, the values of the different parameters being determined by previous experience. To illustrate this point, the observation is of interest that experienced pilots are suffering less from motion sickness in real flight than student pilots, whereas they are more prone to simulator sickness than student pilots. The internal model of an experienced pilot apparently has parameter settings that match quite well the motion signals which are sensed by the sensors during real flight, but they do not match to the information as sensed by the sensors in, for instance, a fixed-base simulator environment. For student pilots the argument goes the other way around: they have no particular experience as for the in-flight environment. Thus, in the simulator the match is better then during real flight, where they sense motion signals which are not expected.

To summarise, difference vectors between sensed and expected linear and rotatory motion are not a trigger for motion sickness: this may only result in disorientation. Only differences between the sensed and expected vertical provoke motion sickness.
This is illustrated in modern architecture where fully listed buildings are popping up more and more: In a stationary listed environment (visual frame information not coinciding with the gravity vector) head movements were found to be provocative to motion sickness. This was described by Kitahara & Uno [30] and we confirmed this observation: Walking in a stationary listed environment (max. 20 degrees) made about 10% of the subjects motion sick within 15 minutes. Especially the turning around proved to be provocative [11]. In this condition it is noteworthy that a stationary subject doesn't get motion sick, despite the continuing conflicting information from the visual frame and the otoliths about the direction of the vertical. According to the SV conflict model, the sensed and the expected attitude converge due to the feedback in this situation: Only when the subject starts to move around, differences are to be expected between these two vectors. This is a common observation in many motion sickness provoking surroundings: Moving around or making head movements enhances motion sickness (see section 2).

4. Factors causing nausea in virtual environment simulators

Somatosensory-visual-vestibular interactions. With the principle of the subjective vertical mismatch one can analyse the different virtual environments concepts on provocativeness for motion sickness. To illustrate the meaning of this concept, the results of laboratory experiments which are of direct relevance for the use of HMD and VE system concepts, are shown in Fig. 3. The results stem form experiments done by Brandt et al. [14] and Bles [5].
In these experiments the magnitude of the nausea of the Coriolis effect obtained by lateral head tilt during constant velocity rotation at 60 □/s was studied under different visual and somatosensory stimulus conditions. The pure vestibular Coriolis effect, head tilt in darkness, served as a reference and had a magnitude of 5. It shows that the Coriolis effect is minimal if there is sight on the earth-stationary visual surround. This is comparable to walking conditions with a HMD with a perfect earth-stationary virtual environment. The nausea increases if the visual surround rotates together with the chair, which is compatible to rotating with a HMD with a head fixed display. If the surround rotates with twice the chair velocity, the nauseating effect of a head tilt is very strong. This demonstrates what happens if the HMD provides non-earth referenced motion information. Inspection of the right frame in Fig. 3 indicates that

manipulation of somatosensory motion information as obtained by stepping in circles in darkness provides similar results as manipulation of the visual information when sitting. If in these conditions the visual and optokinetic motion information is combined, the modulation of the vestibular Coriolis effect is even more pronounced (Fig 3 right frame, open dots). This shows how important it is to take into account the somatosensory information, if present, otherwise the analysis may lead to predictions which are completely different from the experimental data. The Subjective Vertical model as shown before fully accounts for these experimental results [6]. The SV model also perfectly applies to the concept of the closed cockpit aircraft [11].

Fixed base vs. moving base. In order to minimise simulator sickness for HMDs with virtual environment applications, the same rules apply as for fixed and moving base simulators. Moving in a virtual environment of a HMD may be accomplished by turning or walking on a treadmill, or by means of a joy-stick. These changes of propagation means, together with irregular motion velocity patterns using the joy-stick may even be more demanding from the human equilibrium system than a normal 6DoF flight simulator. In fact, keeping in mind the frequency characteristics of the different parts of the equilibrium system, the model in Fig 1 may help to analyse the stimulus patterns on their provocativeness to motion sickness. It is no surprise that a HMD training facility on board of a moving platform with motion which has absolutely nothing to do with the training scenario, is due to be more provocative than on a non-moving platform.

Destabilisation of the visual world. If one makes a head movement while wearing a HMD, the image in front of the eyes will move with the head. In other words, in such situations the visual world loses its stability [40].
An additional complication here is that when we make a rotatory head movement, the eyes rotate in the head in counter direction. This so called Vestibulo-Ocular Reflex (VOR) normally serves to maintain ocular fixation on an object in our environment during head movements. The VOR is very fast and has a latency of approximately 10 ms. However, to maintain ocular fixation when the object moves with the head (as in a HMD) the VOR must be suppressed. The necessary enervation of the ocular musculature is relatively slow and frequency specific. With head movements up to 1Hz the VOR can be properly suppressed, but at higher frequencies the VOR dominates, blurring the visual image on the retinas and causing visual discomfort. If the blur stems from very fast retinal motion its direction cannot be perceived, which may have consequences for the computation process as indicated in Fig. 2.

Image magnification (or minimisation). Similar problems may occur when an outside image, projected inside an HMD (e.g. the image of a night vision goggle), is magnified or minimised. Normally the VVOR (VOR with full sight on the visual surround) has a gain of 1, which means that the velocity and amplitude of this reflexive eye movement is equal to that of the counterdirective head movement. If the head movement is fed back to move a magnified image in a HMD in counter direction to the head, the velocity of the image shift is higher than expected, while with a minimised image it is lower. This means that the visual information contributing to the computation in Fig. 2 may not properly match the vestibular inputs in the computations, which may also lead to discrepancies in the determination of the representation of gravity. Such situations resemble the case where one scans the scenery with binoculars in which case the visual image moves across the retinas with a much higher speed than is normally the case during head movements. The same happens when wearing new spectacle glasses. But since glasses are usually worn continuously the visual vestibular interaction may adapt back to normal in due time. However, as long as such adaptation is not complete nausea might persist. Unless one wears a HMD for quite a long time similar adaptation may not easily be obtained. Thus it is recommended not to use a magnification or minimisation factor in the design of VE or HMD visuals with outside image representations.

There is another discomforting problem related to image magnification or minimisation. The point is that when we stand upright we normally make small body movements (body sway). Here the visual system helps. It feeds these small retinal image shifts back to the system which maintains body posture. When those image shifts do not really correspond to how the body really moves (because of their optical magnification or minimisation), they are still fed back to our musculature with which we maintain our postural equilibrium. Thus we may end up making much larger body sway motions, which poses a threat to our postural stability and may create feelings of insecurity with respect to our equilibrium (in fact it is this mechanism which causes fear of heights — in which case the image movements have become disproportionally small, because of the very far distance of objects in the visual environment [13].

Time delays. In many VE simulations head movements are fed back to the visual display, with the purpose of moving the image across the display in the direction counter to the head movement. This should ensure that the virtual environment remains stationary relative to earth (i.e. relative to gravitation and compass-fixed) during head movements. However, in many simulators, including HMD-systems, this coupling is less than perfect, which may cause severe nausea. The point is that the visual image must move across the display surface in precise temporal synchrony with the movements of the head. Otherwise a phase difference between the visual and vestibular inputs to the CV and SV occurs which may cause them to deviate from each other, causing severe nausea. However, it always takes time to record (and filter) head movements and to calculate the movements of the image inside the HMD on the basis of these records. This manifests itself in a temporal delay of the required visual image changes, especially with very large and detailed displays. During the delay period there is a large discrepancy between visual and vestibular information: the head movements are properly registered by the vestibular system, but the visual world moves *with* in stead of *against* the head. Even with delays as brief as 46 ms, the resulting visual-vestibular mismatch, which may easily cause a CV vs. SV mismatch, may already be extremely nauseating [20, 27].

This reasoning is in line with empirical results from recent experiments in which the gain and phase relations of visual and vestibular information were manipulated separately, using an artificial environment set up mounted on a sled for linear motion [32]. The data clearly suggested that phase differences are much more provocative than gain differences, and that, in contradistinction to visual phase-*leads* (relative to the vestibular stimulus), small visual phase-*lags* are already highly provocative.

Vection. Visually induced sensations of self-movement, known technically as "vection", are of course key phenomena in simulators. However, since visual suggestions of self-motion may easily affect the Sv through the integration INT with the SCC and SOM information (see Fig. 2), they always form a potential risk of motion sickness. In this section we will review the properties of visual displays and images that affect vection, and which thus have to be considered in evaluating the risk for the development of nausea in simulators.

Screen size. Vection is strongest with peripherally moving visual flow fields. Hence, large screens carry higher risks of motion sickness. With full-field flow fields almost everyone will experience strong sensations of vection. Thus as a general rule, the smaller the visual image (or display) the lower the chance of motion sickness. From laboratory experiments it has been concluded that the risk of vection is minimal with images extending a visual angle less than approximately 30°. A normal standard 17 inch computer screen viewed at a distance of 50 cm encompasses 34° and therefore will not easily generate vection.

Foreground/background. A necessary condition for vection to occur is that the inducing visual pattern is perceived and interpreted as a background. Normally, when walking past an object which we fixate with our eyes, its background moves in our visual periphery, the central area of the visual field is occupied by the retinally stationary object. However, when we move in a vehicle (e.g. a car), the situation is reversed. Here the peripheral parts of our visual field are occupied with objects that remain stationary on the retinas (e.g. the hood of the car, the frame of the windshield, the dashboard etc). In such situations vection is caused by image motion across the central area of the visual field. Experiments have shown that such centrally evoked vection is possible only if the visual flow is perceived as background, that is, as further away in depth than the stationary objects in the periphery. Hence, in exception to the above mentioned rule, visual patterns covering small visual angles may still evoke vection if they are perceived as a background. Thus small displays in simulators, which simulate "out-of-the-window" views may facilitate vection.

Pattern motion. As should be clear by now, moving visual patterns always carry with them a certain chance that vection develops. With a constant velocity pattern vection normally develops with a latency between up to 20 seconds (depending on various stimulus parameters) after which vection velocity does not increase any further and the pattern appears earth stationary. At this point vection is said to be saturated. The forcefulness with which vection is experienced and the perceived velocity of vection depend not only on the size of the vection inducing pattern, or on whether or not it is perceived as a background, but also on its velocity. Perceived vection velocity increases with the velocity of the stimulus pattern up to approximately 60°/s, after which it is reduced rapidly and the visual pattern is perceived as unstable or just moving.

Vection also depends on the motion frequency of the inducing pattern. As mentioned above, its latency can be relatively long, implying that low frequencies are more powerful than high frequencies. With sinusoidal pattern motion frequencies up to 0.1 Hz vection can normally be induced. At higher frequencies vection rapidly decreases. Thus if one wants to prevent vection it is important to keep this cut-off frequency of 0.1 Hz in mind.

5. Other discomfort factors in head mounted displays

Image flicker. Typical computer work complaints such as eye-strain, visual fatigue, headache and blurred vision, are common also when working with HMDs. The reason for these complaints are not always clear, but one of the causes often suggested is image flicker. Our sensitivity for image flicker is higher in the visual periphery than in the central visual field. Causes for image flicker are long times needed for computing the motion of images in the HMD (update frequency), especially when these computations must be carried out on the basis of on-line head movement registrations, and the refresh rate of the particular screen used in the HMD. It is advisable to avoid screens that have a refresh rate of less than 80 Hz. Traditional video screens are too slow (50 Hz). To reduce the risk of perceiving flicker it is also advisable to reduce the luminance of the images in the HMD to less than 50 cd/cm2 and to keep luminance contrasts relatively low as well.

Image acuity and depth perception. Bad image acuity may also yield complaints of headache and eye-strain, especially when text has to be read. Image screens should have a resolution at least comparable with that of a 1024 × 768 pixel 17 inch computer monitor. Traditional video screen technology has too low a resolution to be acceptable in HMDs, especially with wide angle screens.

With 3D VR systems, the two eyes receive separate and slightly different images, which are fused by the brain to perceive depth. It is advisable to facilitate the fusion process as well as possible, by positioning the image optically at 2 to 4 m distance from the eyes. The necessary ocular accommodation is then 0.5 to 0.25 dioptres and the necessary convergence of the eyes then covers 0.9 to 0.4 degrees of visual angle. If the two images are not placed at the correct position relative to the eyes eye-strain will result from the additional oculo-muscular effort required.

To keep a reasonable visual acuity in such 3D VR and HMD systems, the following criteria should apply with respect to corresponding details in the two images (correct adjustments of the rims of the images is less critical):

- The (rotational) difference between corresponding details should not exceed 1°.
- The vertical position of corresponding details should not exceed 0.5°.
- Divergence between corresponding details should be no more that 0.5°.
- The size of corresponding details should not differ by more than 3%.
- The difference in required accommodation of the two eyes should not exceed 0.25 dioptres.

Smoothness of image motion. To avoid headaches and eye strain in simulators it is necessary that smooth visual motion will indeed be perceived as smooth. This is not always the case. The same factors apply here as those which cause flicker. When calculations necessary for generating moving images take relatively much time (low update rate), or screen refresh rate is low, the movements will be seen as consisting of small steps. This is visually quite discomforting.

Motion parallax. On the flat surface of visual displays there is no real depth. It must be simulated. Not only by proper perspectives which change during simulated ego motion, but more importantly, by concurrent relative motion between the objects in the surroundings (motion parallax). If motion parallax is not properly programmed, it may create impressions of self motion which do not properly fit vestibular cues from the motion base. For example, most simulator systems use visual display systems in which the movements of the vehicle (e.g. an air plane) are fed back to change the visual image on the display in such a manner that it appears stationary with respect to the real world. However, if the head movements of the individual inside the simulator are not fed back to affect the image on the display in a similar manner, the concurrent vestibular sensations may not always match the changes in the image. For example, imagine a person inside such a simulator who moves the head closer to a visual display unit that is supposed to simulate a window through which a visual outside scene is seen. The eyes then get closer to the screens. In normal situations more of the visual environment will then become visible from behind the rims of the window and the size of the retinal images of far away objects will not change much. Conversely, if such a forward head movement is made in a simulator, where the observer's head position is not fed back to the image on the screen, no new parts of the environment will become visible from "behind" the rims of the screen and the images of all virtual objects will be enlarged equally on the retinas, whatever their distance. Therefore the changes in the visual information will not match the vestibularly sensed head movements. This may cause visual discomfort and, if lasting long enough, eye-strain and headache. If that visual-vestibular mismatch includes aspects of the subjective or sensed vertical, a risk of motion sickness may evolve as well.

Control device system lag. When using a computer mouse, a joy stick, roller ball or any other control device to affect the image on a visual display in a simulator which is used in an interactive man-in-the-loop mode, performance may be affected when delays between the action and its effect on the screen become too large. Such delays are not discomforting in the sense that they might cause motion sickness, headaches etc, but they may well have a deteriorating effect on tracking and steering performance.

No hard limits can be given for maximum lags because they also depend on the kind of vehicle model used in the simulator (see for a review: Ricard [37]). However in general steering performance is assumed to deteriorate when control device system lags increase beyond 100 ms [1, 2], while lags over 300 ms may induce oscillations [3]. With respect to normal computer use, lag times for the use of a mouse should not become larger than 50 ms, while the lag between pressing a key on a key-board and the appearance of a letter on the display should not be longer than 100 ms (DERA defence standards [18]).

After-effects. When trainees spend many hours inside a simulator there is a risk of after- effects once they exit the simulator. Such after-effects include not only a continuation of nausea, but also postural imbalance and headaches (see for a review: Wertheim [41]). They may have negative effects on performance in normal everyday behaviour (e.g. driving), or may aversely affect special skills such as are involved in flying an air plane. This issue has been recognised in the literature as having juridical consequences for those responsible for simulators and trainees. They might find themselves liable if trainees cause accidents after a simulator training. Only recently has research started on such after-effects and currently there is not much specific information available as to their exact nature and the risks involved. However, after-effects may last for many hours [3].

6. Conclusions

Head Mounted Displays still easily provoke discomfort. The known visual problems in using HMDs which are due to the technical limitations of the display and computing limitations, will most probably be solved by technical improvements in the near future. As long as that is not the case, the factors described in section 5 should be taken into account.

In developing HMD application concepts one should be aware of the motion sickness consequences of orientation cues which lead to false visual verticals, because of the fact that a discrepancy between the sensed and expected representation of gravity is considered to be the primary motion sickness provoking conflict. Qualitative analysis with the model on the provocativeness of the application taking into account what is known on the sensory interactions is very useful already. Quantitative analyses by Bos & Bles [12] have shown that the model accounts for the sea sickness data of O'Hanlon and McCauley [34]. This is a very promising accomplishment, since the international standards (see section 2) are based on descriptive models.

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