Working in a moving environment

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The present paper provides a review of research and theories concerning the question of how and why working in a moving environment may affect performance. It is argued that performance decrements can be expected to occur as a result of general factors or as a result of specific impairments of particular human skills. General effects happen when environmental motion, simulated or real, reduces motivation (due to motion sickness), increases fatigue (due to increased energy requirements), or creates balance problems. Specific effects of moving environments on task performance may only be expected through biomechanical influences on particular skills such as perception (interference with oculomotor control) or motor skills (such as manual tracking). There is no evidence for direct effects of motion on performance in purely cognitive tasks.

1. Introduction

With the current fast rate of technological developments, the use of simulators, especially moving-base simulators, is rapidly increasing. They are used especially for purposes of training to carry out tasks and work in moving environments, such as aircraft, road vehicles and ships. This has created many challenges for human factors researchers, who are often asked to investigate such questions as the validity of the simulators or the efficiency of training procedures. It is surprising, however, that much of the research carried out with simulators assumes that we know how work is actually carried out in a moving environment. This is not always the case. Many investigators are only dimly aware of research on how movement affects performance. To help them fill this gap, the present paper presents a review of what is currently known about the nature of human performance in moving environments, both in simulators and real environments. It has not been the intention to describe in detail all published material on these issues. Instead the idea is to summarize current knowledge, and to provide references for those who want to obtain more detailed information.

The review is structured along a classification of the effects of environmental motion on performance in terms of two categories: general effects and specific effects. General effects refer to any task, any performance, carried out in a moving environment. Such effects may be of a motivational nature (motion sickness), of an energetical nature (motion-induced fatigue caused by the continuous muscular effort to maintain balance), or of a biomechanical nature (interference with task performance because of a loss of balance). Specific effects, on the other hand, refer to interference with specific human abilities (e.g. cognition, perception, etc.).
2. General effects of environmental motion on performance

2.1. Motion sickness

There are various kinds of motion sickness, such as sea sickness, car sickness, air sickness, space sickness, and some people are sick in trains or even in elevators. A particularly noteworthy kind of motion sickness is simulator sickness, occurring frequently both in fixed and in moving-base simulators as well as in virtual environment situations.

2.1.1. Motion sickness in general: One of the best-known phenomena occurring in a moving environment is motion sickness. It causes a massive lowering of motivation, usually resulting in a considerable slowing down of work rate, a disruption of continuous work and often its complete abandonment. Sensitivity to motion sickness varies widely among humans. For example, tolerance to sea sickness is very high with children a few years old, is then reduced and at old age increases again. Furthermore, sea sickness may develop fast or slowly, depending on the individual, while some people appear to be resistant to it. Women are generally somewhat more sensitive than men. It is also known that motion sickness in a long duration motion environment usually decreases with time (generally referred to as adaptation). Adaptation may take a few hours — as in centrifuge-induced motion sickness (see below) — or a few days, as with sea or space sickness. However, the time it takes for the symptoms to disappear may vary with circumstances, such as the type of wave movements, and differs among individuals. With approximately 5% of humans adaptation to sea sickness does not take place at all (see Colwell (1989) for some reviews of these issues).

It is not really possible to test a person’s general sensitivity to motion sickness. Within individuals, there is no direct correlation between sensitivity to the various forms of motion sickness (Bles et al. 1984). Nevertheless, 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 (Kennedy et al. 1968).

This is not the proper place to present a detailed description of how the vestibular apparatus works. Many good texts on the subject are available elsewhere (Guedry 1974, Howard 1986). Here it suffices to note that the central role of the vestibular system is recognized in what is currently the most well-known theory of motion sickness (Reason and Brand 1975), usually referred to as the Theory of Intersensory Mismatch.

According to this theory, motion sickness occurs when the vestibular apparatus provides the brain with information about self-motion that does not match precisely the sensations of self-motion generated by other sensory systems (such as the visual or kinaesthetic systems), or what is expected from previous experience.

We have two peripheral vestibular systems, one in each inner ear. Each one consists of several sub-systems: linear accelerations (in the vertical gravitational direction, in the horizontal forward/backward direction, and in sideward directions) are picked up by two otoliths. Rotational accelerations along those three axes are picked up by three semi-circular canals, which lie in different orthogonal planes. Hence, sensory mismatches may also occur within the vestibular apparatus itself.

The mismatch theory has its shortcomings, and in recent years alternative theories have been formulated. For example, a recent view is that motion sickness
does not occur when there is a sensory mismatch concerning perceived self-motion, but when there is ambivalence about the perceived vertical (Bles and De Graaf 1993). Although this theory deviates from the traditional view, it is related to the traditional theory, because the perceived vertical is influenced by self-motion. There are some other alternative theories (Stoffregen and Riccio 1986, Yardley 1992, Oman 1982), and there are ideas about cognitive influences on motion sickness (Dobie and May 1994). However, here we will take sensory mismatch theory as our point of departure, as it is still the most widely accepted theoretical approach in the literature on motion sickness, and it explains a large variety of motion sickness phenomena.

To illustrate the theory, consider the situation of a person inside a closed cabin on a ship at sea. The motions of the ship are picked up by the vestibular apparatus and they inform the brain that the head (i.e. body) moves in space. The visual system, however, perceives a stationary environment, as the walls of the cabin do not move across the eyes (i.e. the retinae). Consequently vestibular and visual information about self-motion are not identical. This is a typical sensory mismatch situation where motion sickness may easily develop (Hettinger et al. 1990).

The theory also explains some remedies for motion sickness. For example, in the case of a ship at sea, it is well-known that providing the visual system with an optic pattern that remains stable relative to the world (e.g. a horizon as seen on deck or through a large window) reduces the incidence and severeness of motion sickness. In fact there have been some attempts (Rolnick and Bles 1989, Bles et al. 1991) to investigate possible motion sickness reducing effects of an artificial horizon. In these studies the artificial horizon consisted of a line, projected across the walls of a ship’s cabin, which moved in synchrony with the ship’s pitch (forward-backward tilting) movements and roll (leftward-rightward tilting) movements. Another option — which is still rather speculative, as it is only based on some informal observations of the author, but which is related to the above mentioned theory about the subjective vertical — is to try and hold one’s stance aligned to the real (gravitational) vertical.

In a ship’s cabin, this may require a kind of balancing act that makes the body (and therefore the head) move quite strongly relative to the walls of the cabin, thus providing the visual system with at least some optic flow across the eyes, consistent with the ship’s motion.

In a famous series of experiments, carried out in a Ship Motion Simulator (SMS), McCauley et al. (1976) suggested that it is mainly the vertical component of ego motion (heave motion) that causes motion sickness. They found that with sinusoidal motions of frequencies between 0.05 to 0.8 Hz and accelerations of more than 1 m s$^{-2}$, maximum sensitivity to motion sickness happened at around 0.2 Hz, the incidence of sea sickness increasing further at higher accelerations. Their mathematical model of motion sickness has long been the most generally accepted one within the research community concerned with motion sickness (see also O’Hanlon and McCauley 1974).

However, more recently other mathematical models have been proposed. The best known one was proposed by Griffin (1990), which deals not exclusively with sinusoidal movements, but also with other types of motion (for a comparison of these two models and some theoretical extensions concerning adaptation, see Colwell 1994).

The main premise of all these models is that small purely vertical accelerations (below 1 m s$^{-2}$) have not much potential to generate motion sickness. In a series of experiments with the SMS of the TNO Human Factors Research Institute (for
technical details see Bles and Vunderink 1994, Bos et al. 1995), this was found to be true (Wertheim et al. 1995a). However, the severity and incidence of motion sickness (measured with a rating scale, see De Graaf et al. 1992, Wertheim et al. 1992) increased dramatically when such small vertical movements were accompanied by low frequency pitch and roll motions with amplitudes ranging between 12 and 14°. In addition, separate or combined pitch and roll movements in the absence of any vertical motion appeared to be sickness provoking as well, albeit to a lesser extent.

A problem with such SMS experiments is that we do not know exactly how the subjects move their heads when inside a simulator. This prevents a proper description of how the vestibular and visual systems are stimulated. This is illustrated in another study (Wertheim et al. 1995b), where subjects were not required to sit on chairs, but had to carry out a physical task that included bending the body (they had to move and pile crates). In this study, motion sickness incidence was very high (reaching 50%). This supports the view that intra-vestibular mismatches such as coriolis effects may play an important role in the generation of motion sickness (Reason and Brand 1975, Eyeson-Annan et al. 1996).

Motion sickness may also develop as a result of horizontal linear movements (Golding and Kerguelen 1992, Horii et al. 1993). In this respect it should be noted that motion sickness is also a problem encountered in space. Many astronauts suffer from it, especially during the first few days of a flight. Space sickness presumably stems from the fact that the linear acceleration sensors (the otoliths) are deprived of their normal constant gravitational acceleration stimulus. Conversely, but in line with this reasoning, Bles et al. (1989) observed that when subjects in a human centrifuge are submitted to a constant hypergravity acceleration (2 or 3 g) for some time (one to several hours), they may feel quite motion sick upon their return to normal gravity, especially when making head movements. Astronauts participating in these studies recognized the symptoms as similar to those of space sickness (Bles et al. 1989, Ockels et al. 1990).

2.1.2. Simulator sickness: As mentioned above, a special case of motion sickness is simulator sickness. A well-known review has been published by Kennedy et al. (1988), who defined simulator sickness as motion sickness associated with simulated movements that in real life are not motion sickness provoking.

Simulator sickness can be quite strong in fixed-base simulators, especially if the visual display is very large (e.g. a dome). In terms of sensory mismatch theory this happens because the movements of the visual environment create strong sensations of ego motion that are not matched with concurrent vestibular sensations of self-motion. Actually, this is one of the reasons why much effort has been invested to create moving-base simulators, which, it was hoped, should provide those vestibular sensations and thus reduce motion sickness.

However, in many cases these hopes appear to have been over-optimistic, as several factors in moving-base simulators still cause sensory mismatches. For example, on the flat surface of visual displays there is no real depth. It must be simulated. Not only by proper perspectives that 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 that do not properly fit vestibular cues from the motion base. Another example, sometimes encountered in moving-base simulators, is that the programmed point of view of the observer inside the
simulator relative to the visual display is incorrect. During horizontal rotatory movements of the simulator (e.g. when ‘taking a turn’ with a tank simulator), the environment then moves in a way different from that which the visual system of the observer expects on the basis of vestibular information provided by the moving base. A similar problem occurs when the environment is programmed to rotate with its centre of rotation located wrongly (e.g. at a location different from the real point of rotation of the rotating simulator cabin).

A severe coupling problem, often causing nausea with subjects wearing head-mounted virtual environment displays, is that the visual image must move across the display surface in temporal synchrony with the movements of the head. To attain this, head movements must be recorded and on the basis of these records the movements of the presented image must be calculated. This takes time, especially with very large and detailed visual displays. If the delay becomes longer than something like 20 ms, the resulting visual-vestibular mismatch may become extremely nauseating. In a recent experiment the gain and phase relations of visual and vestibular information were manipulated, using an artificial environment set-up, mounted on a linear acceleration sled (Mesland et al. 1996, 1998). The results showed that phase differences are much more nausea provoking than gain differences, and that in contradistinction to visual phase lags relative to the vestibular stimulus, small visual phase leads are not nausea provoking.

However, even with properly programmed very fast computer systems that create close to perfect visual surrounds, visual-vestibular mismatches cannot always be prevented because of the very nature of moving-base simulators. The point is that with most simulators strong or long duration linear accelerations cannot be generated; they must be simulated. For instance a forward or backward linear acceleration is usually simulated by tilting the simulator cabin backward or forward, to create a situation where subjects feel being ‘pressed’ backward or forward into their chairs. Although this may, on somatosensory and cognitive levels, create the suggestion of a linear forward or backward acceleration (especially with the proper visual display) such tiltings actually consist of rotations. Rotations are sensed by the semi-circular canals, which normally do not react during linear accelerations. The consequent erroneous tilting sensations are usually suppressed by the linearly moving visual surround. When the motion frequencies are rather low (as with commercial aircraft simulators) the sensory conflict is generally too weak to cause problems, i.e. there is little risk of motion sickness. However, with higher frequency movements (as with fighter aircraft or road vehicle simulators) this suppression implies a really strong visual-vestibular mismatch, increasing the risk of motion sickness. A similar reasoning applies with large or long duration horizontal rotations (e.g. road curves), which are usually simulated by tilting the simulator cabin sideways, activating the ‘wrong’ semi-circular canals. A related problem happens when the simulator is repositioned back to its horizontal zero position to be ready for the next manoeuvre. This repositioning should be done very slowly, such that the concurrent vestibular stimulation (usually called the ‘wash-out’) remains below threshold. Otherwise a strong visual-vestibular mismatch happens, as wash-out movements are of course not present in the visual display. The problem with such slow below threshold wash-outs is that they are possible only when the simulated vehicle movements have very low frequency characteristics (e.g. with large civil aircraft). With fast military aircraft simulators or road vehicle simulators, movements usually have much higher frequency characteristics, making slow wash-out
motions impossible. Thus in such simulators it is extremely difficult, if not impossible, to avoid visual-vestibular mismatches caused by above threshold wash-out movements of the moving base.

2.2. Balance problems
Motion of the platform on which one works affects postural control and this may interfere with normal human performance and locomotion. Only quite recently has research begun on balance problems on ships or in ship motion simulators (Graham 1990, Baitis et al. 1994, 1996). Usually this kind of work is concerned with people standing in upright position while instances of (near) loss of balance (usually referred to as Motion Induced Interruptions, or MII's) are recorded.

Such MII records have been used in combination with biomechanical models of the human body to build models that predict the frequency of MII’s for a standing person during particular ship movements or sea states (Graham 1990, Lewis and Griffin 1995, Baitis et al. 1994, 1996). Models like these can be used to generate criteria as to when it is safe or dangerous to perform particular tasks on ships (e.g. on the platform of an aircraft carrier).

Only in a few cases did these studies involve subjects who do not stand, but who walk (Wertheim et al. 1993, 1994). Since MII models do not apply as yet to walking humans, these data may be of relevance to an extension of current MII theorizing.

Actually, for MII research, motion is not always necessary. MII’s can also be measured on a stationary tilted floor, and there is at least one report—related to emergency procedures aboard listing ships—in which such effects have been described (Wertheim 1993).

2.3 Physical fatigue
It is a well-known fact among people who work on ships that they are more easily fatigued when doing physical work at sea, than when the same work is done ashore. In the scientific literature relatively little attention has been given to this phenomenon, known as Motion Induced Fatigue (MIF, Colwell 1989). Only a few attempts have been made to empirically investigate MIF. This is probably because many members of the human factors community are trained as psychologists, which might incline them to study mental rather than physical fatigue. However, physical fatigue is likely to affect mental performance as well. Hence the study of MIF and its development should be quite useful.

A strong incentive to the study of MIF has come from a recent multinational research programme, sponsored by the ABCD (American, British, Canadian and Dutch) Working Group on Human Performance at Sea (Baitis et al. 1995). In this programme the method used to measure physical fatigue in quantitative terms was taken from the field of exercise physiology. Here physical fatigue is generally deduced from measuring oxygen consumption of the human body during physical work. These are quite complex experiments in which inhaled and expired breathing air must be analysed, together with a number of other physiological measures. The amount of oxygen consumed is then expressed as a percentage of the maximum capacity for oxygen consumption. That maximum must be measured in a separate test (a so-called maximum performance or graded exercise test), which must be carried out a few days prior to the actual experiment. This percentage—usually referred to as ‘relative physical work load’—appears to be mathematically related to the maximum time a subject can carry out the work (Bink 1962, Louhevaara et al.
This maximum time can thus be used as a fatigue index: it indicates how long one can still carry on with a particular task from the time the measurement took place.

An early attempt to measure oxygen consumption in a moving environment was carried out with subjects inside a ship motion simulation facility (Crossland and Lloyd 1993, Crossland 1994, Baitis et al. 1994, 1996). In this study the subjects were standing. They were not actively involved in physical work, and no maximal tests were carried out. The results showed a slight increase in oxygen consumption during the simulated ship movements. However, the increase was much less than expected, given the fact that the subjects appeared to be very tired at the end of the experiment (Crossland 1994). In three other studies (Heus et al. 1994, Wertheim et al. 1993, 1994, 1995b, Heus et al. 1998), oxygen consumption was measured inside the SMS during walking on a treadmill or across the floor of the simulator cabin, or during a crate stacking task. In these cases, prior to the experiments, the subjects did perform maximum performance tests outside the simulator. Nevertheless, the results were similar to the earlier finding: when the fatigue index was calculated — on the basis of the amount of oxygen consumption expressed as a percentage of maximum capacity for oxygen consumption — again only a relatively small increase in fatigue was found. The increase was still too small to explain that, when they exited the SMS after experimentation, the subjects gave the impression of being severely fatigued.

On the basis of these findings the hypothesis was put forward that inside a moving environment oxygen consumption during the work itself may indeed be only slightly increased, but the body’s maximum capacity for oxygen consumption might be reduced. In two additional experiments (Wertheim et al. 1996a, b) this hypothesis was tested. This time subjects performed two maximal tests. One test was carried out inside a stationary SMS, the other inside a moving SMS. The two maximal tests were separated by 1 week from each other and both were carried out 1 week or more before the actual experiment. During the actual experiment, the task inside the moving SMS consisted of riding a bicycle ergometer for 4 h at a fixed energy level (30% of maximum capacity as determined prior to the experiment outside the SMS). The results did indeed support the hypothesis: maximum capacity was significantly reduced in the moving SMS. When the oxygen consumption data from the cycling task was expressed as a percentage of this lower maximum capacity level, fatigue appeared to be increased by approximately 100%. In other words, inside the moving SMS the maximum time during which subjects would be able to keep cycling until exhaustion was halved as compared to when the task was carried out in a stationary SMS. The finding that maximum oxygen consumption during a maximal test is reduced in a moving environment was recently replicated in another SMS experiment (Wertheim et al. 1997). Thus it is reasonable to assume that working inside a moving environment may indeed be at least twice as fatiguing as working in stable surroundings.

3. Specific effects of a moving environment on performance

So far, the possibility has been discussed that a moving environment affects performance through general intervening motivational, biomechanical or energetic variables. Such effects apply basically to any kind of task performance. An alternative approach is to investigate specific effects of environmental motion on task performance, i.e. to ask whether environmental motion by itself specifically affects particular human skills.
3.1. Complex tasks
When asked to investigate performance in a moving environment, the kind of tasks human factors researchers are most likely to be confronted with are real tasks, such as those carried out in aircraft, or on bridges and in technical (command) centres of ships. However, such tasks are usually quite complex in terms of the psychological skills required, and this is probably why research on effects of movement on such complex tasks is hard to find. Recently two such experiments have been carried out in an SMS (Helsdingen 1996, Wertheim and Kistemaker 1997). The complex task was a simplified version of a real naval task, requiring decisions on the basis of interpretations of radar images from which particular information had to be memorized. Information had to be sampled by clicking a mouse button (after positioning a cursor at particular locations) to reveal hidden codes. Thus the task consisted of an interplay of cognitive skills (decisions had to be made on the basis of memorized information), perceptual skills (small codes had to be read next to target locations), and fine motor co-ordination skills (precise manual positioning of the cursor and clicking on small target symbols). In such complex tasks, performance cannot be analysed in terms of the classic one-dimensional parameters that are normally used as performance indices, such as reaction times or number of correctly detected signals. Instead a general system-analytical parameter was used, reflecting the amount of information transferred from the task to the human operator. Both studies showed that with a moving SMS, a small but significant reduction of information transfer happened.

Of course the problem with such an effect is that it cannot be explained as motion-induced interference with any one particular human skill. Hence one should be careful to make generalizations to other tasks with different skill structures. The solution of this problem is not easy: for most complex tasks the skill structure is basically unknown, which is a common problem in ergonomics.

The obvious way out is to use only relatively simple tasks in which the human skills required are obvious. When taking this approach, one line of reasoning is to distinguish three classes of tasks on the basis of their underlying skill components:

1. cognitive tasks (e.g. attention, memory, pattern recognition);
2. motor tasks (e.g. manual tracking, fast button press reactions); and
3. perceptual tasks (e.g. visual or auditory detection).

In the literature there appear indeed to be several attempts to study possible effects of environmental motion on task performance, attempts that take the above distinction as their point of departure. They will be reviewed here.

3.2. Cognitive tasks
Bles and Wientjes (1988) studied the effect of a moving environment (tilting room) on a cognitive memory comparison task. They observed no effects. In another study (Bles et al. 1988), which consisted of a 1-day sea trial aboard a ship, the same memory comparison task was used. Again no effects of ship motions were observed (there was a small decrease in performance, but this was more likely to be the result of sea sickness, as it disappeared when the severity of sea sickness decreased during the day). More recently, Bles et al. (1991) again studied task performance aboard a ship at sea, this time during a 2-day sea trial. Again they used the same memory comparison task. Although initially it appeared that reaction times increased slightly
with an increase in the magnitude of the ship's movements, this increase too disappeared later on during the sea trial. Thus, from these studies it seems that there is little or no effect of environmental motion on cognitive performance.

Crossland and Lloyd (1993) mention similar findings (see also Crossland 1994, Baitis et al. 1994, 1996). They report on an experiment in which effects of environmental motion were studied on a variety of cognitive paper-and-pencil tasks, carried out inside a moving SMS. It appeared that these cognitive tasks did not suffer from the simulated ship movements.

Other indications that cognitive abilities are not affected by ship movements stem from three separate studies performed in an SMS. In the first experiment (Wertheim et al. 1995a) subjects were asked to perform a digit addition task. In a second study (Wertheim et al. 1995b) subjects carried out a variety of cognitive and visuo-motor tasks. More recently an experiment was performed (Wertheim and Kistemaker 1997) in which subjects had to carry out either a visual or a cognitive task (together with the complex task mentioned in §3.1). In none of these experiments was any effect of (simulated) ship movements observed with any of the cognitive tasks.

Most tasks mentioned in the literature are rather short. They are carried out typically for periods lasting from a few minutes to half an hour at most. However, there is at least one report of a study about effects of simulated ship motions on performance on a long duration (several hours) radar monitoring task (Malone 1981). That task included a strong attentional, and thus cognitive, component. However, in that study too, no motion-induced performance decrement was observed.

Given these reports, the conclusion appears warranted that cognitive skills are not directly affected by ship movements. However, it is possible that some indirect effects of environmental motion could happen in cases where cognitive tasks require much effort, e.g. because they make a very high demand on short-term, or working, memory (Gaillard and Wiëntjes 1994, see also Hockey 1997). Performance on such tasks may be affected only slightly or not at all, but when indices of mental effort are used concurrently, such as a reduction of sinus-arithmy, they might show that in a moving environment more mental effort is required than in a stationary one. If so, this could explain the small effects of environmental motion on the complex cognitive task mentioned above (Helsdingen 1996, Wertheim and Kistemaker 1997). That task seems to rely more on very short-term memory processes than the standard memory comparison tests, as used in the above-mentioned sea trials or tilting room study. The author is currently investigating this issue in a new series of experiments in an SMS.

3.3. Motor tasks
In what was probably one of the first studies carried out in a ship motion simulator, McLeod et al. (1980) asked subjects to carry out various motor co-ordination tasks involving arm, hand and finger movements. Performance was degraded to the extent that the required motor activity was of a fine control rather than of a ballistic nature. The suggestion that ship movements may interfere with fine motor performance was also supported by the above-mentioned SMS study with paper-and-pencil tests, reported by Crossland and Lloyd (1993; see also Crossland 1994, Baitis et al. 1994), where some motion-induced performance-degrading effects appeared to occur with tests requiring fine motor control. More
recently, performance on a visuo-motor task in the above-mentioned study by Wertheim et al. (1995b), where a computerized tracking task was used, also showed a decrement due to motion of the SMS.

On the other hand Bles and Wientjes (1988) had, in the above-mentioned 1-day sea trial, also included a manual visuo-motor tracking task, and they reported no effect. However, the ship motions encountered during this sea trial were rather mild. During their later 2-day sea trial Bles et al. (1991) again included a tracking task, but only compared performance during separate periods of particular ship movements. They found no differences in performance, but comparisons with baseline performance data (obtained in calm waters) could not be made, as these were lost. Hence, their conclusion was only that if there is a degrading effect of ship movements on manual tracking, it did not vary with the kinds of ship movements encountered during their sea trial.

In conclusion, it seems that ship movements interfere to some extent with fine motor control, but not necessarily always. It is reasonable to assume that when these interfering effects happen, they are caused by biomechanical factors.

3.4. Perceptual tasks
As mentioned before, Malone (1981) with his long duration radar monitoring task (which of course was not only cognitive, but also to a large extent perceptual) observed no motion-induced performance decrement. This suggests that perception is not affected by ship movements.

However, although perception itself may not be affected, biomechanical effects may indirectly impair perceptual performance. For example, in an experiment with subjects seated in a rotating chair, Wientjes and Bles (1989) studied the effects of passive body rotation on performance in a visual search task (the visual display was attached to the chair and thus remained head-stationary). A decrease in performance was observed. However, the authors attribute the effect to the fact that sufficiently strong rotary accelerations of the head, as used in their experiment, induce reflexive nystagmoid eye movements, which blur the image on the stimulus display.

The same explanation may hold for an effect observed by Wertheim and Kistemaker (1997), who used a visual performance task in their SMS study, in which subjects had to identify a particular target letter presented within briefly visible arrays of letters on a computer monitor. With large letters there was no effect, but with small letters a significant performance decrement was observed.

Thus, effects of (simulated) ship movements on perceptual skills may stem from visual blur, caused by the reflexive nystagmoid eye movements that are known to accompany vestibular stimulation. However, such reflexive eye movements need not be the only biomechanical factor affecting visual perception. Small high-frequency vibrations, such as are known to happen in aircraft (most notably helicopters), may cause the eyes to slightly vibrate in their sockets. If so, dashboard displays or control panels vibrate across the eyes. This blurs the visual image. Such vibrations may also occur aboard particular ships or in ship motion simulators (for some reviews on such vibratory effects see Guedry 1974, Moseley 1986, Moseley and Griffin 1986, Von Gierke et al. 1991, Griffin and Hayward 1994).

In conclusion then, from the literature on specific effects of a moving environment on task performance it appears that such specific effects may be expected only to the extent that biomechanical factors are of relevance. Hence tasks requiring good (oculo) motor control may suffer, but one should not expect specific
effects on performance characterized by other components (Rolnick and Gordon 1991).

Seen in the light of this conclusion one may assume that the motion-induced performance degradation in the above-mentioned complex task used by Helsdingen (1996) and Wertheim and Kistemaker (1997), could — apart from a possible loading of short-term memory — also have stemmed from biomechanical interference with visual perception (reading the small codes in the target locations) and with fine motor control (cursor steering).

4. Conclusions

Research on motion-induced performance decrements shows that such decrements can be expected to occur when motion creates general artefacts such as reduced motivation (due to motion sickness), balance problems, or increased fatigue (due to increased energy requirements). On the other hand, specific effects of moving environments on cognitive performance have as yet to be demonstrated. If one looks at concurrent indices of mental load, however, one might have a chance to find some evidence for motion-induced interference. In contrast with this apparent absence of motion effects on cognitive performance, it is quite likely that, through biomechanical factors, motion interferes with fine motor control or with the perception of small visual detail. These factors should be taken into account when considering human performance in moving environments, such as ships, aircraft or moving-base simulators.

References


Baitis, A. E., Holcombe, F. D., Colwell, S. L., Crossland, P., Colwell, J. and Pattison, J. H. 1994, 1991–1992 Motion Induced Interruptions (MII) and Motion Induced Fatigue (MIF) experiments at the Naval Biodynamics Laboratory. Technical report CRDKNSWC-HD-1423-01, Carderock Division, Naval Surface Warfare Center, Bethesda, MD, USA.

Baitis, A. E., Holcombe, F. D., Colwell, S. L., Crossland, P., Colwell, J., Pattison, J. and Strong, R. 1996, 1991–1992 Motion Induced Interruptions (MII) and Motion Induced Fatigue (MIF) experiments at the Naval Biodynamics Laboratory. Technical report for the ABCD Working Group on Human Factors at Sea, Carderock Division, Naval Surface Warfare Center, Bethesda, MD, USA.


Colwell, J. L. 1994, Motion sickness habituation in the naval environment. DREA Technical Memorandum 94/211, Canadian National Defence Research Establishment Atlantic, Dartmouth.


Dobie, T. G. and May, J. G. 1994, Cognitive-behavioral management of motion sickness, Aviation, Space and Environmental Medicine, 65 (10), section II, C1 – C20.


Gaillard, A. W. K. and Wientjes C. J. E. 1994, Mental work load and stress as two types of energy mobilization, Work and Stress, 8, 141 – 152.


LEWIS, C. H. and GRIFFIN, M. J. 1995, Modelling the effects of deck motion on postural stability. ISVR Contract report 95/12, May, Institute of Sound and Vibration Research, University of Southampton, UK.


