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ILLUSORY SELF MOTION AND SIMULATOR SICKNESS

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INTRODUCTION

According to the sensory conflict theory of motion sickness, spatially and/or temporally decorrelated perceptual information specifying one's dynamic orientation in space can lead to disorientation and sickness. The underlying conflict may either be intra- or intersensory in nature. Intrasensory conflict can arise, for instance, from decorrelated information within the vestibular system, such as that which accompanies Coriolis stimulation. Intersensory conflict can be caused by spatially and/or temporally decorrelated visual and vestibular information, such as that which occurs in flight simulators.

Simulator sickness is a form of motion sickness in which users of vehicular simulators exhibit signs and symptoms generally characteristic of motion sickness. In a fixed-base flight simulator, visual and vestibular sources of information specifying dynamic orientation are decorrelated to the extent that the optical flow pattern viewed by the "pilot" creates a compelling illusion of self motion which is not corroborated by vestibular information. Visually induced illusory self motion is known as "vection" (Tschermak, 1931) and a strict interpretation of sensory conflict theory makes vection in a fixed-base simulator a necessary precondition for simulator sickness.

This paper presents a discussion of simulator sickness (with applications to motion sickness and space sickness) based on the notion of the senses as perceptual systems (Gibson, 1966), and the sensory conflict theory (e.g., Reason & Brand, 1975). Most forms of the sensory conflict theory unnecessarily propose the existence of a "neural store." The neural store is thought to consist of a record of previous perceptual experiences against which currently experienced patterns of stimulation are compared. This paper seeks to establish that in its most parsimonious form the sensory conflict theory does not require a construct such as the neural store. In its simpler form, the sensory conflict theory complements and extends Gibson's view of the senses as perceptual systems.

I propose that motion and simulator sickness are produced by a breakdown (i.e., conflict) in the normal relationship between individual sub-systems of a functionally unitary perceptual system. The "orientation system," consisting primarily of the visual and vestibular sub-systems, is most directly implicated in the etiology of motion and simulator sickness. While in the case of simulator sickness illness may primarily be due to a breakdown on the stimulus side (i.e., decorrelated visual and vestibular information), in other cases disorientation and sickness can be produced by alterations in the normal activity of the physiological mechanisms that underlie the perception and maintenance of orientation (i.e., altered vestibulo-ocular reflex response in space sickness). Therefore a complete account of motion sickness, simulator sickness, and space sickness must address questions concerning the "what" (i.e., the stimulus side) and the "how" (the neurophysiological side) of the phenomenon.

The sensory conflict theory also interacts well with most empirical and theoretical accounts of adaptation to perceptual distortion and perceptual learning. For instance, it is well known that, with time, humans and other animals adapt to the stimulus conditions that underlie motion sickness (Money, 1970), simulator sickness (Kennedy, Hettinger, & Lilienthal, 1990), and space sickness (Thornton, Moore, Pool, & Vanderpleg, 1987). Following adaptation to a nauseogenic force environment, readaptation to a previously benign force environment must occur and often results in a number of related perceptual-motor disturbances (e.g., land sickness, postural disequilibrium following simulator flights). Furthermore, the symptoms of disorientation, vertigo, mental confusion, and sickness that are characteristic of these maladies can be conceived as being due to a violation of normal multisensory relationships to which a lifetime of perceptual learning have made us uniquely sensitive.

The final section of this paper discusses a proposed experiment to be conducted on the U.S. Army's Crew Station Research and Design Facility at NASA Ames Research Center. The purpose of the experiment is to clarify the relationship between the experience of illusory self motion and the occurrence of simulator sickness, as well as to test the hypothesis that the onset of sickness in the simulator is preceded by a breakdown in the normal activity of postural control. This latter idea has been recently introduced by Stoffregen and Riccio (Personal Communication), and represents the first major new theoretical approach to motion sickness since the emergence of the sensory conflict theory.

SIMULATOR SICKNESS

This paper discusses the problem of simulator sickness, especially as it relates to the perception and control of self motion. A major purpose of the paper is to propose an experiment which could be conducted to clarify the relation between illusory self motion, or vection, postural instability, and simulator sickness.

Background

Motion sickness is a familiar, highly unpleasant condition which can occur when susceptible individuals are exposed to various provocative force environments, such as at sea, in space, in the air, and in vehicles on land. The capability to simulate aerial self motion has produced a new form of motion sickness referred to as "simulator sickness" (Kennedy, Hettinger, & Lilienthal, 1990; McCauley, 1984). Simulator sickness closely resembles "true" motion sickness (i.e., sea or air sickness), but is generally less severe and often involves visually-related disturbances (e.g., blurred vision, eyestrain) that are rarely observed in other forms of motion sickness (Ebenholtz, 1988).

Flight simulation has become an invaluable tool in the training and maintenance of aviator skills and in the research and development phases of aircraft design. This is due primarily to its inherent safety and cost effectiveness (Orlansky & String, 1977a; 1977b), as well as the wide range of training and research scenarios that can be utilized. However, an apparent increase in the occurrence of simulator sickness threatens to diminish the utility of this technology for training and research and development.

Recent technical developments in flight simulation have stressed the use of large field-of-view visual displays of the out-of-the-cockpit scene using highly realistic imagery. The intent is to provide the user with a high degree of "felt presence" in the simulated environment. In parallel with, and possibly as a result of these technical developments, the reported incidence of discomfort, illness, and prolonged negative aftereffects among simulator users has steadily increased (Kennedy et al., 1990).

Simulator sickness may significantly limit the training and research capabilities of flight simulators. Illness is likely to have a negative effect on performance and learning, thereby contaminating research data and rendering training effectiveness questionable. When sickness is particularly frequent and severe, it may be necessary to restrict pilots' post-simulator flight activities, thereby diminishing their operational readiness. Pilot trainees may also adopt compensatory perceptual-motor strategies to avoid sickness in the simulator that will result in poor transfer of training to the aircraft. For example, pilots may restrict head movements in the simulator in order to minimize the occurrence of optokinetically-induced illness from pseudo-Coriolis effects (Dichgans & Brandt, 1973).

Symptoms of motion sickness are known to occur in the presence of visual stimulation alone with no concomitant physical movement (Dichgans & Brandt, 1978; Lestienne, Soechting, & Berthoz, 1977). Occurrences of illness while viewing Cinerama (Benfari, 1964) and other wide field-of-view motion displays (Parker, 1971) have been reported. For example, Lestienne, Soechting and Berthoz (1977) reported that subjects experienced intense, disturbing sensations of motion sickness induced by viewing large field-of-view, high velocity motion patterns. Three subjects out of thirty (10%) in their study became so disoriented while viewing these motion patterns that they fainted. The common element among these situations is the powerful, illusory sensation of self motion, referred to as "vection," experienced by the observers.

Vection, a term first used by Tschermak (1931), refers to the illusory sensation of self motion induced by viewing optical flow patterns that are specific to the form of self motion experienced. Vection can be induced in any of the body's linear or rotational axes (Dichgans & Brandt, 1978). Illusions of this sort are known to occur in non-laboratory conditions, such as the illusion of sudden forward motion induced by the perception of the backward motion of an adjacent automobile. Evoked responses in the vestibular nuclei of the rabbit (Dichgans & Brandt, 1972), cat (Daunton & Thomsen, 1976), and monkey (Henn, Young, & Finley, 1974) have been observed in response to vection-inducing stimuli, suggesting that such stimulation "recruits" activity in this area.

Until recently it was generally accepted that large field-of-view motion displays with substantial coverage of the peripheral retina were most effective in producing vection (Dichgans & Brandt, 1978). Andersen and Braunstein (1985), however, obtained reports of vection and motion sickness with centrally presented motion displays subtending visual angles as small as 7.5 deg. They asserted that an adequate representation of motion in depth may be as important as field-of-view size in eliciting vection. Brandt, Wist and Dichgans (1975) obtained evidence indicating that the apparent motion of objects in depth is a powerful determiner of vection.

Reason and Brand (1975) hypothesized that in many cases conflicting inputs from visual and vestibular afferents are responsible for the occurrence of motion sickness. Intrasensory conflict (i.e., conflicting signals from the otoliths and semicircular canals) may also, in some cases, produce motion sickness. This "sensory conflict" theory would predict that visually induced apparent motion in the absence of corroborating vestibular motion information will produce motion sickness. To the extent that a visual stimulus depicts motion but does not also elicit vection, a conflict does not exist. Vection thus would appear to be a sine qua non for simulator sickness in fixed-base simulators according to this model. Individuals who report little or no illusory self motion in a fixed-base simulator should show little illness. The converse is not necessarily the case, because some individuals may be insensitive to such conflicts.

Previous experimentation on vection and sickness.

An experiment was recently conducted by Hettinger, Berbaum, Kennedy, & Nolan (in press) at the U.S. Navy's Visual Technology Research Simulator to investigate the relationship between vection and simulator sickness. Eighteen college student volunteers served as experimental observers. Each was asked to sit passively and observe three 15-minute computer generated representations of motion over a simulated 3-D terrain as presented on a large field of view (40 deg vertical, 80 deg horizontal) color visual display.

The motion trajectory presented to the observers was designed to be as nauseogenic as possible in order to assure that a sufficient number of observers experienced some symptoms of optokinetically-induced illness. It has been demonstrated that the most effective motion frequency for inducing sea sickness is slightly below 0.2 Hz (McCauley & Kennedy, 1976). Frequencies in this range were therefore selected for displacement in the vertical, longitudinal, and lateral axes, as well as for roll, pitch and yaw variations. All observers viewed the same motion patterns.

During the observation period, observers were asked to rate the degree of self motion they experienced on a scale of 0 - 3 (where 0 = "no feelings of self motion," 1 = "slight feelings of self motion," 2 = "moderate feelings of self motion," and 4 = "strong feelings of self motion"). Observers were also monitored for symptoms of simulator sickness using the Motion Sickness Questionnaire (Kennedy, McCauley, & Pepper, 1979) and also by means of an electrophysiological measure known as the electrogastrogram or EGG (Stern, etc.). The EGG measures the pacesetter potential of the stomach, which under normal circumstances is approximately 3 cycles/minute. When an individual becomes nauseated the EGG increases to a frequency of 11 - 15 cycles/minute,

The results indicated a clear and consistent relationship between the experience of illusory self motion and the occurrence of sickness. Those observers (approximately half) who reported no symptoms of sickness also reported little or no experience of illusory self motion. On the other hand, those observers who did experience sickness consistently reported moderate to strong sensations of self motion.

Visually-specified illusory self motion clearly represents a situation in which the normal activity of the orientation system is interrupted. Years of perceptual learning render most animals highly attuned to very specific temporal and spatial relationships between inputs from the visual and vestibular sub-systems. The coordinated, correlated activity of these sub-systems results in effective perception and maintenance of orientation and self motion.

Violation of these temporal and spatial constraints on the perception and maintenance of orientation appears to be the necessary prerequisite for disorientation and sickness. The evidence indicates that this is the case in flight simulators, in provocative terrestrial force environments, and in space sickness.

Discussion

Symptoms of motion sickness normally occur only in response to some form of physical displacement (e.g., motion at sea or in the air) with concomitant stimulation of the vestibular system. Therefore it may seem somewhat surprising to observe similar symptomatology in a fixed-base flight simulator in which no physical displacement occurs, but which may nonetheless provide compelling impressions of self motion.

The neural interrelationships between the visual and vestibular systems, primarily through the vestibular nuclei, have been the focus of a great deal of study in recent years (e.g., Precht, 1979). As I have argued above, it is generally useful to conceptualize visual and vestibular proprioception as manifestations of an integrated perceptual system (Gibson, 1966) designed to maintain orientation in space and control of self motion. Through a combination of heredity and a lifetime of perceptual learning, this system becomes attuned to spatial and temporal information which is highly correlated. The introduction of temporally asynchronous or distorted spatial information into the system appears to produce sensations of disorientation and illness in susceptible individuals

Simulations of in-flight visual motion patterns vary in the extent to which they elicit illusory sensations of self motion. Some provide veridical representations of optical flow patterns (Owen, 1982; Warren & Owen, 1982) characteristic of flight that do not lead to the illusion of self motion, while others appear to give rise to compelling experiences of vection. Researchers disagree on the requirements of visual displays for producing illusory self motion (e.g., Andersen & Braunstein, 1985). Nevertheless, the distinction between the perception of a depicted path (trajectory) and velocity of a point of view through a depicted space with no concomitant experience of illusory displacement, may be one of the keys to understanding the underlying causes of simulator sickness. Visually-specified, illusory self motion may entail a significant vestibular element while the perception of a display representing viewpoint motion without illusory displacement may not. A number of studies (e.g., Held, Dichgans, & Bauer, 1975; Mauritz, Dichgans, & Hufschmidt, 1977) have demonstrated large effects of rotating visual displays on postural sway. Observers in these studies continually readjusted their stance to compensate for visually-specified displacements of gravito-inertial upright. Lestienne et al. (1977) reported similar effects with patterns representing linear motion.

The relevance of these studies and the one reported here for the design of flight simulators lies in the demonstration that visual displays of motion patterns which produce vection produce more simulator sickness. In order to alleviate simulator sickness and related aftereffects it may be advantageous to: (a) investigate the training utility of displays which do not produce illusory self motion, and/or (b) identify the underlying causes of sickness in displays that produce vection so they can be eliminated.

EXPERIMENTATION ON THE CREW STATION RESEARCH AND DESIGN FACILITY

Riccio and Stoffregen (1989) argue that simulator sickness, and other varieties of motion sickness, are due to prolonged interference with postural control. Their model states that: "Postural control will be disrupted in the simulator to the extent this it is based on simulated motion (e.g., optic flow) that is not related to the dynamics of balance in the simulator cockpit" (Riccio, 1989, p.12). The probability of sickness occurring in the simulator is therefore proportional to the amount of postural disruption.

Riccio and Stoffregen's model represents an opposing view to the sensory conflict theory. In particular, they object to the construct of the neural store which plays a central role in many versions of the conflict theory. Their model hypothesizes that a rather different form of conflict underlies the occurrence of disorientation and sickness. This conflict lies in the separate demands placed on strategies of postural control by the visual and somatosensory sub-systems of the orientation system.

By contrast, the version of the sensory conflict theory that I have argued for perceives the conflict to lie not at a motor control level, but at a somewhat more primitive sensory level. It is interesting to note that both models' predictions with regard to simulator sickness are best enhanced under a particular stimulus situation, i.e., with a highly effective (in terms of inducing sensations of self motion) visual depiction of self motion that has no corroborating somatosensory component.

The two models differ with regard to the predicted precursor signs of simulator sickness. The sensory conflict theory asserts that a powerful experience of the illusion of self motion is a necessary precondition for the occurrence of sickness in a fixed base simulator. The postural-instability model, on the other hand, would predict that sickness would be preceded by postural readjustments driven by the motion specified on the visual display. To the extent that postural readjustments are not observed (i.e., pilots' heads and torsos are restrained, or pilots simply do not respond to the visual display) sickness should not occur. Sensory conflict theory would predict that sickness would be largely independent of any postural control activity, although the experience of vection is often accompanied by postural control activity. We have endeavored to construct an experimental situation which would test the predictions of the two models.

Design

An exploratory experiment to evaluate these separate models of simulator sickness is proposed to be conducted on the U.S. Army's Crew Station Research and Design Facility (CSRDF) at NASA Ames Research Center. The CSRDF consists primarily of a fixed-base LHX helicopter simulator with a head-slaved helmet-mounted display that has a wide field-of-view (110 deg horizontal by 60 deg vertical).

During experimental trials the simulated aircraft will move at a constant speed and altitude over the simulated terrain. The terrain model in the CSRDF is produced using a General Electric Compuscene IV Computer Image Generation System, and provides a very realistic representation of highly textured terrain. During flight the aircraft will be subjected to roll-axis disturbance, generated by a sum of three to seven harmonically unrelated sinusoids. The disturbance power will be concentrated in the frequency range between .01 and 1.0 Hz.

In some conditions, the pilot's head and torso will be restrained to reduce demands on postural control. The torso will be restrained with an upper body harness, while the head will be restrained with the use of a cervical collar. Continuous ratings of the strength of illusory self motion will be obtained using either a verbal rating scale or a suitably rigged potentiometer.

Data will be collected during each trial on aircraft states, pilots' flight control actions, head movements, and physiological measures of discomfort. These latter measures include the electrogastrogram, electrocardiogram, blood volume pulse, respiration, skin temperature, skin conductance, and eye movement activity. Post-flight measures will include tests of postural equilibrium to assess ataxic effects of simulator exposure. Ataxia, or postural disequilibrium, is a common sign of simulator sickness (Kennedy et al., 1990).

The pilot's task will be to either visually track an object that is not along the direction of motion, maintain the head and upper torso in an erect posture, or maintain a straight and level attitude in the presence of the disturbance function. In the first two cases the pilot will have no control over the activity of the aircraft.

Five sets of dependent variables will be obtained: 1.) subjective measures of vection and discomfort, 2.) physiological measures of discomfort, 3.) manual control measures of disturbance regulation performance, 4.) measures of postural stability in the simulator, and 5.) measures of gait stability outside the simulator. Data analysis will concentrate on correlating magnitude estimates of vection and indices of postural control (i.e., head movement data) to our measures of sickness. Manual control data will also be analyzed for the disturbance regulation trials.

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