the orientation of the vehicle is described in engineering terms as a multidimensional "state vector" consisting of the vehicle's angular and linear position, velocity, acceleration, and often other factors. Engineers are frequently confronted with the problem of controlling a vehicle's complete orientation state vector when information from sensors that measure these states is noisy, and many dimensions of the vehicle state vector are not directly measured at all. It is a complex multi-input, multi-output control problem. To deal with it, engineers now routinely incorporate into the control system design a computational element known as an "observer" (as shown in Fig. 1), whose function is to continuously provide a running estimate of the orientation state vector of the vehicle being controlled. Control loops are closed using the estimated orientation state vector provided by the observer, since simple direct feedback of actual vehicle orientation state in the traditional way is not possible. Analytical techniques were developed (Kalman 1960; Wonham 1968) for mathematically linear systems that allow designers to choose observer and control loop parameters so that the observer state estimate is always converging with reality and which optimize the closed loop performance of the entire system. In control engineering parlance, such systems are formally called "output feedback" optimal control systems.

Of particular importance in the present context is the way in which the observer estimated orientation state vector is calculated in these engineering systems. The observer contains an internal "dynamic model" of the controlled system and of the orientation sensors being used. The observer element uses these models to calculate what the actual feedback sensor measurements should be, assuming the vehicle orientation state estimate of the observer is correct. The difference between the expected and the actual feedback measurements is then computed, because it is the error in the measurement prediction and is also an indirect measure of the error between the estimated and actual vehicle orientation. This difference is itself a vector. It is used by the observer to steer the estimated observer vehicle orientation state towards reality, i.e., the actual vehicle orientation state vector. This is done using a method described in more detail later. Eventually, the error in the predicted measurement will fade to the level of the measurement noise when the outside disturbing forces cease and provided the basic structure of the observer internal models is correct. In practice, a sustained high level of error in the predicted measurement is a clue to the designer that the differential equations that are the observer internal dynamic models might be in need of revision.

There is a direct analogy between the "expected" feedback sensor measurement and "internal dynamic model" concepts in control engineering observer theory, and the "efference copy" and "neural store" concepts of von Holst and Reason. The CNS must infer the body's orientation and control body movement using a limited set of noisy sensory signals. From the perspective of control engineering, the problem is familiar. One can infer that the "orientation" brain must "know" the natural behavior of the body, i.e., have an "internal model" of the dynamics of the body and maintain a continuous estimate of the spatial orientation of all of its parts. Based on observer theory, incoming sensory inputs should be evaluated by subtraction of an "efference copy" signal, and the resulting "sensory conflict" signal used to maintain a correct spatial orientation estimate as shown in Fig. 2. By analogy, the "actual orientation" vector might here consist of the angular

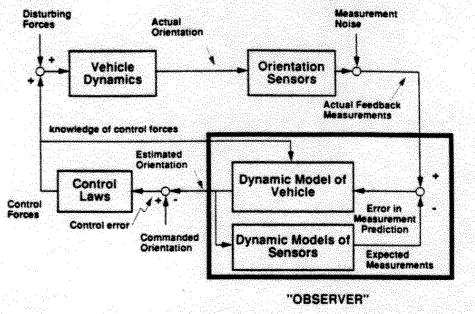

FIG. 1. Engineering use of an "observer" to control vehicle orientation. Solid arrows represent multidimensional vector quantities. Orientation sensors are noisy and do not directly measure all aspects of orientation which need to be controlled. Vehicle must follow orientation command signals in spite of exogenous disturbing forces.

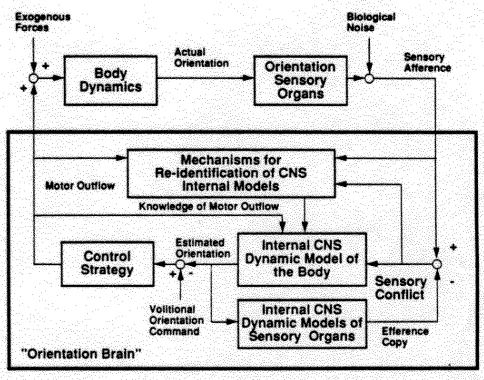

FIG. 2. Mathematical model for sensory conflict and movement control based on observer theory (Oman 1982). Note that the structure parallels Fig. 1.

and linear displacements of all the parts of the body and higher derivatives. The "internal CNS dynamic models" are the differential equations describing the body and sense organ dynamics. Based on the knowledge of current muscle commands, the internal model equations are used to compute an "estimated orientation" state vector, which determine new muscle commands based on "control strategy" rules, as indicated in the figure. Simultaneously, the "estimated orientation" state is used by the CNS sense organ model to compute an "efference copy" vector. Normally, the efference copy vector nearly cancels polysensory afference. When it does not, the difference (the "sensory conflict" vector) is used to steer the model predictions towards reality and indirectly to trigger corrective muscle commands. These functions represent a critical functional role for conflict signals in daily life. Clearly, we need not postulate that sensory conflict signals exist just to make people sick.

In normal life, we experience exogenous forces only briefly (e.g., when we stumble over an obstacle), so increases in sensory conflict are normally only temporary. Sustained sensory

conflict would be expected under conditions of sustained exogenous motion, as when one is a passenger on a moving vehicle. It would also occur if the input–output dynamic characteristics of the sensory organs or the body itself were suddenly changed, i.e., conditions of "sensory rearrangement" (Reason 1978; Held 1961). People experience such conditions when, e.g., they enter weightlessness, don vision distorting spectacles, fly a fixed base flight simulator, or live in a rotating environment. A sustained high level of sensory conflict indicates that the CNS needs to revise the observer internal model differential equations to match the prevailing conditions. Presumably the CNS monitors the average level of sensory conflict, and when it is high, the dynamic model equations are adjusted so that average conflict is reduced. This "model reidentification" process is a form of sensory–motor learning. It represents a second important daily functional role for conflict signals in daily life which is unrelated to the emetic process. Presumably, the CNS observer can retain multiple sets of previously learned internal models and employ them in the appropriate context.

Exactly how an observer sensory conflict vector might be used to steer internal model predictions is described briefly below and in Fig. 3. Readers who are familiar with matrix algebra will recognize that the large number of linearized differential equations describing relevant components of the body's neuromuscular and sensory systems can be represented in a much more compact shorthand using state variable notation as a set of matrix equations. Additional details are available in Oman (1982, Appendix 1). The equations have the form

$$[1]\quad \dot{\underline{x}} = A\underline{x} + B\underline{u}$$

$$[2]\quad \underline{a} = S\underline{x} + \underline{n}_a$$

$$[3]\quad \underline{u} = \underline{m} + \underline{n}_e$$

These equations are represented graphically in the upper half of Fig. 3. The coefficients of the state differential equations for body and sense organ dynamics are embodied in the matrices A, B, and S. The center block is a vector integrator. Note that the state variables from both the body and sensory organ models are combined in the vector $\underline{x}$. Mathematically there is no essential reason to distinguish between body and sense organ dynamics, although this was done earlier for clarity in Fig. 2. The internal CNS dynamic models of Fig. 2 are represented by an analogous state differential equation shown in the bottom half of the figure. CNS observer estimates are denoted using hatted variables. This "hatted variable" state estimator with its matrices $\hat{A}$, $\hat{B}$, and $\hat{S}$ corresponds to the "neural store" of Reason's (1978) more qualitative model. The sensory conflict vector $\underline{c}$ is obtained by subtracting actual sensory input $\underline{a}$ from expected sensory input $\hat{S}\hat{\underline{x}}$. Sensory conflict normally only originates from exogenous motion cue inputs $\underline{n}_e$ and sensory noise $\underline{n}_a$. The conflict vector is multiplied by a matrix K calculated using an optimization technique defined by Kalman and Bucy (1961), which lightly weights noisy modalities. When the result is added to the derivative of the estimated state, the estimated state vector is driven towards the actual state, and the component of the conflict vector magnitude due to noise is reduced.

Note also that the observer anticipates the effect of motor commands on the rate of change of the estimated state via the term $\hat{B}\underline{m}$. Because of this term, active body movements (as

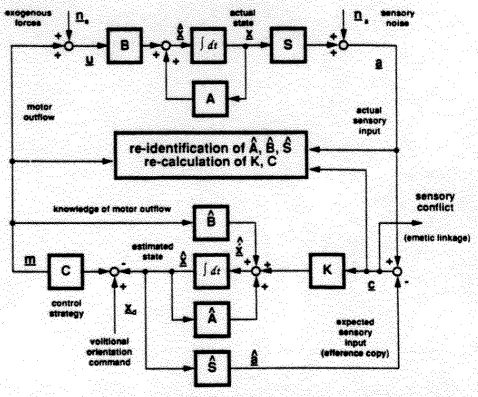

FIG. 3. Mathematical formulation of model shown in Fig. 2 (Oman 1982). The observer continuously estimates body orientation. The matrices $\hat{A}$, $\hat{B}$, and $\hat{S}$ correspond to the "neural store" of Reason's (1978) qualitative model. The sensory conflict vector $\underline{c}$ is obtained by subtracting actual sensory input $\underline{a}$ from expected sensory input $\hat{S}\hat{\underline{x}}$. See text for additional details.

when running, jumping, dancing) do not cause increased sensory conflict; only exogenous forces (as when riding as a vehicle passenger) and sensory rearrangements do. We can assume that experienced drivers and pilots consider their vehicles extensions of their own bodies by using an appropriately augmented internal model. They therefore would correctly anticipate the effects of their own control commands on their orientation state and experience no increase in sensory conflict. In contrast, the same vehicle orientation changes would be experienced as exogenous forces by the passengers, who have no means of motorically anticipating their motion.

The existence of conflict related motion sickness symptoms, the difference in susceptibility between pilots and passengers, the ability of the contemporary theory to explain it, and the likelihood that conflict signals trigger sensory motor adaptation provide strong arguments that conflict signals actually exist in the CNS, at least for certain sensory modalities. However, it should be emphasized that the argument cannot be extended as presumptive evidence for the physical existence of signals corresponding to the efference copy vector $\hat{\underline{a}}$. The net efference copy effect might in fact be distributed between several feedback loops acting in parallel, none of which contains a signal which, by itself, exactly cancels sensory input. (See Oman, 1982, Fig. 9*b* for an example.) We shall return later to consider how conflict signals might be physiologically identified later (Conclusions), after considering the nature of the emetic linkage.

Experiments on the dynamic character of symptoms and signs

Before discussing models for the emetic linkage response pathways, however, it is appropriate to summarize the results of several experiments conducted in our laboratory during the past decade (Bock and Oman 1982; Oman and Cook 1983; Oman et al. 1986; Oman 1987; Rague and Oman 1987; Eagon 1988). One purpose of these studies was to define the dynamic

character of the emetic linkage and response pathways. We used several different types of stimuli, including out-of-rotation plane "Coriolis" head movements while sitting, eyes closed, in a rotating chair, and head movements while walking about wearing left–right vision reversing prism goggles. Nausea and subjective overall discomfort assessment was accomplished via magnitude estimation. We measure facial pallor and temperature and an observer simultaneously assesses overall sickness level using the Pensacola diagnostic index methodology (Graybiel et al. 1968).

We have found that the latency of response of our individual subjects varies somewhat between repeat test sessions. However, after threshold is reached, an individual subject usually shows a similar pattern of onset, crescendo, and remission of symptoms in each session. Roughly two-thirds of our subjects showed a consistent prodromal pallor which usually correlated temporally with the appearance of stomach discomfort or nausea. (Some of these consistently show a transient blush before the onset of pallor.) As stomach discomfort or nausea first develops, facial pallor begins to deepen, gradually at first and then more rapidly. Facial skin temperature decreases follow, reaching 2–3°C for moderate pallor, lagging by 5–10 min. When the stimulus is first removed, nausea fades rapidly to a low level and may disappear. However, if this first stimulus is strong enough (in terms of magnitude and duration) to elicit a moderate pallor response, skin color returns to normal only gradually.

We frequently ask subjects to participate in experiments lasting several hours. Nauseogenic stimuli are applied at intervals, with rest periods in between to allow symptoms to subside. We consistently find that when the provocative stimulus is reapplied after sickness is well established by previous stimulation, the nausea reappears much sooner, and its subsequent crescendo is more rapid. After the stimulus has been removed, and nausea has faded away, a residual pallor and skin temperature decrease (when present) usually provide a reliable cue that the subject remains in a hypersensitive condition and will require considerable additional time to recover completely. It is as if a physiologic shift responsible for mediating pallor (and presumably many other concurrent physiological changes) takes many minutes to fully develop, but once this shift is established, the subject is demonstrably more sensitive to subsequent provocative stimulation. When pallor, nausea, and overall discomfort are well developed, subjects occasionally report waves of nausea that are no longer temporally correlated with the stimulus, and that persist after its removal. When the sensitized state is reached, many subjects find it difficult to pace themselves without vomiting unless they ask for long rest periods. Many other types of nauseogenic stimuli which previously seemed relatively innocuous suddenly become noticeably provocative. One subject, who was wearing left–right vision reversing goggles and had been standing with his eyes closed and feeling virtually no nausea moments before, stumbled on a curb and, as a result, vomited moments later. Another goggles subject reported that the disparity between the seen and audible position of others talking produced twinges of nausea. A third goggles subject who had been resting for several minutes while his discomfort decreased was then asked to draw the face of a clock on a blackboard and was so disturbed by the disparity between the seen and commanded behavior of his hand, that he vomited with little warning. Almost all of the symptomatic subjects in Eagon's (1988) study reported that filling out a written questionnaire or assembling structures on a tabletop using soda cans while wearing prism goggles was provocative.

A revised model for symptom dynamics

The author's (1982) motion sickness model included nonlinear dynamic elements in the path between sensory conflict and overall discomfort and nausea in motion sickness. This model has since been altered in some important details; the current version is shown in Figs. 4 and 5.

The input to this portion of the model is the sensory conflict vector from Fig. 3. Because of the bandwidth requirements imposed on signals involved in orientation perception and posture control, it seems likely that the components of the conflict vector are neurally coded. In the nausea model, the various conflict vector components (describing the visual, vestibular, proprioceptive modalities) are rectified and then weighted and added together. The result is referred to as the "neural mismatch signal," to correspond to Reason's (1978) model. Rectification is required because sensory conflict components are signed quantities, as Reason and I have defined them. The information carried in the sign is presumably useful in correcting orientation perception and posture control errors. However, stimuli that presumably produce sensory conflicts of opposite signs produce the same type and intensity of nausea, as far as we can tell. Hence rectification is appropriate here. In weighting the various conflict components, vestibular conflicts (i.e., semicircular canal and otolith modalities) must be weighted relatively heavily in the model, since people without vestibular function seem to be functionally immune. Visual motion inputs (as in wide screen movie and simulator sickness) may thus exert their major sick-making effects indirectly: visual inputs would create illusory movement and thus cause vestibular efference copy signals so sensory conflicts would be produced in the heavily weighted vestibular modality. However, to be consistent with our experimental evidence that visual and proprioceptive conflicts under prism goggle sensory rearrangement eventually become provocative while writing or block building, *absent* any concomitant head motion or vestibular conflict, the visual and proprioceptive modality model weighting factors should not be zero. The implication, of course, is that even those who lack vestibular function may have some small degree of subliminal visual and proprioceptive emetic coupling. Even if the vestibular sensory conflict signal paths in these people are inactive, their functional immunity to all forms of sickness may be because visual and proprioceptive conflict alone is insufficient to drive nausea pathways above subliminal levels owing to the lack of the vestibular contribution.

As shown in Figs. 4 and 5, the neural mismatch information acts via two parallel, interacting pathways (containing "fast" and "slow" dynamic elements, respectively) before reaching a threshold – power law element and resulting in a nausea magnitude estimate model output. Magnitude estimates are assumed to be governed by a power law relationship (Stevens 1957) with an exponent of about two. Susceptibility to motion sickness is determined in the model not only by the amount of sensory conflict produced, but also by the fast and slow pathway gains, time constants, and the nausea threshold. The transfer of a generalized adaptation from one different nauseogenic stimulus situation to another might result from adaptation in these output pathways.

The parallel arrangement of the fast and slow pathways and