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Analysis of driver's head tilt using a mathematical model of motion sickness

Takahiro Wada [a], *, Satoru Fujisawa [b], Shunichi Doi [b]

[a] *College of Information Science and Engineering, Ritsumeikan University, 1-1-1 Noji-higasi, Kusatsu, Shiga, 525-8577, Japan*
[b] *Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa, 761-0396, Japan*

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A B S T R A C T

It is known that car drivers tilt their head toward the center of a curve. In addition, drivers are generally less susceptible to carsickness than are the passengers. This paper uses a mathematical model to investigate the effect of the head-tilt strategy on motion sickness. It is shown that tilting the head in the centripetal direction reduces the estimated motion sickness incidence (MSI), defined as the percentage of subjects who vomited. In addition, the head movements of both drivers and passengers were measured in a real car. It is also shown that the estimated MSI of the drivers is smaller than that of the passengers. Experimental results presented in previous studies demonstrated that the severity of motion sickness was reduced when passengers imitated the head tilt of the driver. These results strongly suggest that the driver's head tilt reduces motion sickness, and this can be understood as a subjective vertical conflict.

1. Introduction

Drivers receive both acceleration and rotational stimulation when negotiating a curve, and it is known that they will tilt their head toward the center of the curve. There are various possible interpretations of the reason for this; for example, it may be to obtain fine visual information about the road geometry (Zikovitz and Harris, 1999). It has also been found that the head movement of passengers is opposite to that of the driver, that is, they tilt their heads in the direction of the centrifugal force (Zikovitz and Harris, 1999). Because passengers tend to be more susceptible to carsickness than are drivers, we assumed that the driver's head movement is related to a decreased likelihood of carsickness and a corresponding increase in comfort. Thus, it is expected that an analysis of drivers' active head-tilt motions can lead to the design of a vehicle with a more comfortable motion.

There are many theories about the possible mechanisms of motion sickness (Golding and Gresty, 2005; Shupak and Gordon, 2006). For instance, it has been postulated that increased instability of postural control increases motion sickness (Riccio and Stoffregen, 1991). The eye-movement hypothesis states that motion sickness can be understood as the result of eye movements controlled by the vestibular system (Ebenholtz et al., 1994). Sensory conflict theory (or neural mismatch theory) is well known, and it postulates that conflicting sensory information leads to motion sickness (Reason, 1978; Shupak and Gordon, 2006); this conflict is due to a mismatch between what the individual senses and what was expected. This conflict is thought to be equivalent to the difference between information obtained by the sensory system and the estimated value composed by the efference copy (Reason, 1978). Oman (1982) proposed a mathematical model for sensory conflict theory, in which motion sickness is estimated by connecting the conflict to the averaging process. The structure of this model, in which the conflict is thought to be at the sensory level, agrees with the evidence of neurobiology (Cullen, 2004). Bles et al. (1998) proposed subjective vertical conflict (SVC) theory, in which the error between the sensed and the estimated vertical direction is considered as the source of the sensory conflict. Bos and Bles (1998) proposed a mathematical model of SVC theory for one-dimensional passive motion. Kamiji et al. (2007) expanded this method to six-degree-of-freedom (6-DOF) motion in three-dimensional (3D) space; they incorporated the semicircular canal and the canal-otolith interaction to allow us to deal with head tilt. They also incorporated a measure of the accuracy of the body motion sensations, including the effect of the efference copy, to deal with the difference between drivers and passengers in the degree of control of the vehicle. Given this mathematical model, it is possible to estimate the motion sickness incidence (MSI), which is defined as the

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* Corresponding author.
E-mail address: twada@fc.ritsumei.ac.jp (T. Wada).

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percentage of individuals who vomited due to a given motion stimulus (McCauley et al., 1976). The model uses information about the acceleration and angular velocity of the head to estimate the MSI for a given head motion.

Rolnick and Lubow (1991) discussed the potential factors contributing to the difference in motion sickness between drivers and passengers, namely, controllability, perceived control, activity, visual information, and predictability. Drivers can anticipate their motion in the near future by observing the road geometry and by their active participation in controlling the vehicle. This results in a difference between drivers and passengers in the conflict between sensed information and its estimation from the efference copy. This is similar to the hypothesis of Reason (1978), which is that the difference in the susceptibility to motion sickness occurs because the driver possesses an efference copy related to vehicle control. Visual information also affects anticipation of the motion of the vehicle, and it is known that the wider visual field available to a passenger riding in the front seat also decreases motion sickness (Griffin and Newman, 2004). Also, as mentioned above, drivers tilt their head toward the center when negotiating a curve, whereas passengers tilt their head in the opposite direction. Wada et al. (2012, Wad and Yoshida, 2015) demonstrated that when passengers tilt their head toward the centripetal acceleration, imitating the tilt of the drivers' head, this significantly decreases motion sickness. However, there have been no studies of the effect of the driver's head tilt from the viewpoint of sensory conflict theory.

Therefore, the purpose of this study is to analyze the effect of head tilting by drivers and passengers. To do this, we will use the mathematical model proposed by Kamiji et al. (2007), which is based on SVC theory. First, we introduce a mathematical model for head movement in 3D space. Then, the effect of head movement on motion sickness is investigated by applying the mathematical model to both simulated head movements and head movements measured in experiments with real cars.

2. Mathematical model of MSI based on subjective vertical conflict theory

2.1. Subjective vertical conflict: Theory and a mathematical model

The sensory rearrangement theory of motion sickness is well known (Reason and Brand, 1975; Reason, 1978). This theory postulates that situations that provoke motion sickness are characterized by conditions of sensory rearrangement in which there is a conflict between the motion signal transmitted by the visual, vestibular, and somatosensory systems and that which is expected from previous experiences for adapting to new environments. Bles et al. (1998) proposed SVC theory, in which the error between the sensed and estimated vertical or gravitational directions is the source of the conflict. That is, the conflict is defined as the discrepancy between the vertical direction sensed by the vestibular system and the estimate of the vertical direction by the internal model (Merfeld et al., 1999) that is thought to be built in the central nervous system to resolve ambiguities in the neural signals related to sensory processing and motor control. Bos and Bles (1998) proposed a mathematical model of SVC theory for 1-DOF passive motion. We evaluated the validity of the model by using it to estimate the MSIs for various frequencies and accelerations and then comparing the results of McCauley et al. (1976). Note that the model considers only one-dimensional head motion in the vertical direction without rotation. In addition, the model does not include the effect of the efference copy, which was included in Oman (1982), because the model focuses on passive motions.

2.2. Modeling of MSI for 6-DOF head motion

The 6-DOF-SVC model was proposed for motion sickness due to motion in 3D space (Kamiji et al., 2007), as shown in Fig. 1. This model is an extended version of that of Bos and Bles (1998), and it was created by adding the semicircular canal and canal-otolith interaction to the model of Bos and Bles (1998). This allowed the model to include rotation of the head and a block that can be used to determine the accuracy of the sensation of motion, including the somatic sensation and/or the effect of the efference copy.

The inputs to the model are the gravitoinertial acceleration (GIA) $\boldsymbol{f}$, which is defined as

$$\mathrm{f} = \mathrm{a} + \mathrm{g}, \tag{1}$$

where $\boldsymbol{g}$ is the acceleration due to gravity and a is the inertia; note that the resultant acceleration of gravity ($\boldsymbol{g}$) and inertia ($\boldsymbol{a}$) work on the otolith of the ear at the same time, according to Einstein's equivalence principle. The vector $\boldsymbol{f}$ is input to the otolith, and this is represented by the block marked OTO in Fig. 1. The transfer function of the OTO is given by a unit matrix. The vector ω is input to the semicircular canals, which are represented by the block marked SCC in Fig. 1. The transfer function of the semicircular canal that calculates the sensed angular velocity of the head $\boldsymbol{\omega_s} = [\omega_\mathbf{x}, \omega_\mathbf{y}, \omega_\mathbf{y}]^\mathbf{T}$ from the angular velocity $\boldsymbol{\omega}$, is given as follows (Merfeld, 1995):

$$\omega_s^i = \frac{\tau_d \tau_a s^2}{(\tau_d s + 1)(\tau_a s + 1)} \omega^i \quad (i = x, y, z), \tag{2}$$

where τ_a and τ_d are time constants.

The sensed vertical direction in the head-fixed frame $\mathbf{v}_s$ is estimated from the canal-otolith interaction (Bos and Bles, 2002), as eq. (3):

$$\frac{d\boldsymbol{v}_s}{dt} = \frac{1}{\tau}(\boldsymbol{f} - \boldsymbol{v}_s) - \boldsymbol{\omega}_s \times \boldsymbol{v}_s \tag{3}$$

where the time constant is $\tau = 5$ s (Bos and Bles, 2002) and is represented by LP in Fig. 1. In the figure, the lower part of the block diagram shows an internal model of the vestibular system that is thought to exist in the central nervous system. Blocks $\overline{\text{OTO}}$ and $\overline{\text{SCC}}$ denote the internal models of OTO and SCC, respectively. The transfer function of $\overline{\text{OTO}}$ is given by a unit matrix. The transfer function of $\overline{\text{SCC}}$ is given as (Merfeld, 1995)

$$\widehat{\omega}_s^i = \frac{\tau_d s}{\tau_d s + 1} \tilde{\omega}_i \quad (i = x, y, z), \tag{4}$$

where τ_d denotes the time constant, which is the same as that used in eq. (2).

Gains K_a and K_ω represent the estimation errors of the acceleration and the angular velocity, respectively, and these can be understood as being obtained from somatic sensations and/or the effect of an efference copy (Latash, 1998). In the model, we let $K_a = 0.1$ and $K_w = 0.8$, as shown in Table 1. The internal model of LP, which is illustrated as $\overline{\text{LP}}$, is assumed to be identical to LP. The outputs of the internal model are $\widehat{\mathbf{a}}_s$, $\widehat{\mathbf{v}}_s$, and $\widehat{\boldsymbol{\omega}}_s$. The vectors $\Delta\mathbf{a}$, $\Delta\mathbf{v}$, and $\Delta\boldsymbol{\omega}$ denote the error between the sensory information obtained by the vestibular system, for example, $\mathbf{a}_s$, and the information estimated by the internal model, for example, $\widehat{\mathbf{a}}_s$. These discrepancies are decreased by integration with gains $K_{\omega c}$, K_{vc}, and K_{ac}. Finally, the MSI is calculated by using the error between the sensed and estimated vertical direction $\Delta\mathbf{v}$, and the Hill function $(||\Delta\mathbf{v}||/b)^2/\{1 + (||\Delta\mathbf{v}||/b)^2\}$, which models the nonlinear relationship between the MSI and the magnitude of the vertical conflict and the second-order lag with a large time constant $P/(\tau_I s + 1)^2$, as

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