Knowing What's Coming: Unpredictable Motion Causes More Motion Sickness

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Objective: This study explores the role of anticipation in motion sickness. We compared three conditions varying in motion predictability and assessed the effect of anticipation on subsequent illness ratings using a within-subjects design.

Background: Anticipation is thought to play a role in motion sickness by reducing the discrepancy between sensed and expected sensory information. However, both the exact role and potential magnitude of anticipation on motion sickness are unknown.

Method: Participants (N = 17) were exposed to three 15-min conditions consisting of repeated fore-aft motion on a sled on a 40-m rail (1) at constant intervals and consistent motion direction, (2) at constant intervals but varied motion direction, and (3) at varied intervals but consistent motion direction. Conditions were otherwise identical in motion intensity and displacement, as they were composed of the same repetitions of identical blocks of motion. Illness ratings were recorded at 1-min intervals using an 11-point motion sickness scale.

Results: Average illness ratings after exposure were significantly lower for the predictable condition, compared with both the directionally unpredictable condition and the temporally unpredictable condition.

Conclusion: Unpredictable motion is significantly more provocative compared with predictable motion. Findings suggest motion sickness results from a discrepancy between sensed and expected motion, rather than from unpreparedness to motion.

Application: This study underlines the importance of an individual's anticipation to motion in motion sickness. Furthermore, this knowledge could be used in domains such as that of autonomous vehicles to reduce carsickness.

Keywords: motion sickness, multisensory integration, autonomous driving, attentional processes

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INTRODUCTION

Motion sickness is an unpleasant state of discomfort resulting from exposure to motion. It is characterized by a feeling of malaise and symptoms such as sweating, pallor, dizziness, nausea, and eventually vomiting. It is experienced by a large portion of the population at some point in their life, primarily in the form of carsickness or seasickness (Reason & Brand, 1975). Already an undesirable side-effect of various modes of transport, motion sickness could become an even more substantial problem in autonomous vehicles, as passengers rather than drivers are at a higher risk of motion sickness, even more so when engaging in visual nondriving activities (Diels & Bos, 2016).

A multitude of factors influence how motion sickness develops as a result of motion. For instance, motion frequency is well established to influence motion sickness, with frequencies around 0.2 Hz being the most provocative (Donohew & Griffin, 2004; Golding, Mueller, & Gresty, 2001; O'Hanlon & McCauley, 1974). Visual information, or lack thereof such as when reading in a vehicle, can exacerbate motion sickness and has been studied extensively (Griffin & Newman, 2004; Kuiper, Bos, & Diels, 2018; Perrin, Lion, Bosser, Gauchard, & Meistelman, 2013; Probst, Krafczyk, Büchele, & Brandt, 1982). There also exists evidence that an individual's anticipation of the motion influences the extent to which motion sickness develops (Feenstra, Bos, & van Gent, 2011; Rolnick & Lubow, 1991). In this study, we focus on the latter, the effect of anticipation of motion on subsequent motion sickness.

Relatively few studies dedicated to the subject of anticipation to physical motion and subsequent motion sickness exist in the literature.

Rolnick and Lubow (1991) found that when exposed to identical motion on the same motion platform, the participant in control of the motion became less motion sick. This effect was attributed to the participant in control having increased anticipation of the motion, which has also been found to be beneficial for provocative visual stimuli (Levine, Stern, & Koch, 2014). Feenstra and colleagues (2011) found that in a 6-degree-of-freedom flight simulator motion sickness was significantly reduced by providing the participant with visual information about upcoming motion. These studies had the drawbacks of either being between subjects (Rolnick & Lubow, 1991) or of being coupled with another intervention (Feenstra et al., 2011), offering only limited information on the precise role and effect size of anticipation of motion on motion sickness. However, in addition to these studies, the idea that anticipation could play a role in motion sickness is mentioned frequently in the literature. It might potentially explain in part the benefits of vision in carsickness (Bos, Bles, & Groen, 2008; Kuiper et al., 2018; Perrin et al., 2013). However, the exact importance of anticipation in this matter is currently unknown and therefore worthwhile of further investigation.

Interestingly, the root cause of motion sickness has been theorized to be related to anticipation, namely to be a discrepancy between sensed and expected sensory information (Bos & Bles, 2002; Bos et al., 2008; Oman, 1990; Reason, 1978; Reason & Brand, 1975). That is, external perturbations introduce uncertainty in the sensory feedback expected as a result of self-initiated changes in body state (which are estimated using an internal model containing an "efference copy"); the magnitude of that error between sensed and expected is linked to motions sickness. In this article, we will not further explore the model but rather focus on the effects of anticipation on motion sickness in an experiment study.

Therefore, in the present study, we designed a within-participants experiment to investigate the effect of anticipation of motion on subsequent motion sickness. To isolate the effect of anticipation, it was essential to use conditions that were highly identical in terms of motion frequency and intensity. To that end, we used a simple for-and-backward motion that was presented repeatedly (1) at fixed intervals and always in the same direction, (2) at fixed intervals but in a varying direction, and (3) at variable intervals but always in the same direction. Our hypothesis was that conditions that offer motion stimuli that are unpredictable either in direction or in timing will lead to more sickness compared with a condition of motion that is completely consistent and thus allows for anticipation.

METHOD

Participants

Approval by the TNO Human Factors Institutional Review Board on Experiments with Human Subjects was obtained in accordance with the ethical standards laid down in the 2013 Declaration of Helsinki. All participants indicated they were free of vestibular disorders and in otherwise good health and had not been drinking alcoholic beverages during 24 h in advance of the experiment. Prior to the first experimental condition, the experiment was explained and participants signed an informed consent form. A total of 17 participants, 5 males and 12 females, took part in the experiment, ranging in age from 21 to 52 years with an average age of 39.64 (SD = 10.9).

Apparatus

The motion profiles were realized using a cabin moving on a 40-m track by means of 48 wheels (oriented in rows on three sides of each rail—similar to common rollercoaster design). The cabin was moved by being pulled forward or backward by two synthetic (high molecular weight polyethylene) cables driven by two motors positioned on each far side of the track. See Figures 1 and 2 for the track and cabin. The cabin prevented visual and air-flow cues that give information on the occurrence and direction of motion. Inside the cabin, a rally car seat was fixed to the base of platform, offering a headrest and a 5-point safety belt.

Motion Profile and Conditions

The three conditions were all based on repetition of a single displacement of forward

Figure 1. The motion platform and track. The full track was 40 m; however, in the present study, we exclusively utilized displacements of ±9 m.

Figure 2. The inside of the cabin with the car seat and 5-point safety harness. The cabin prevented visual and haptic (via airflow) information on the occurring motion.

and backward raised cosine motion that was repeated for 15 min. The conditions differed by presenting the displacements: (1) at fixed intervals and in a fixed direction (predictable [P]), (2) at fixed intervals but in a variable direction (directionally unpredictable [dU]), and (3) at variable intervals while keeping the direction fixed (temporally unpredictable [tU]). Participants were exposed to the same semi-randomly generated profiles (see Figure 3).

Each single displacement lasted for 8 s and had an amplitude of 9.0 m, corresponding to a peak acceleration of 2.49 m/s^2. Onset and offset were slightly adapted to have a smooth transition to stationary rather than a sudden change in acceleration. In conditions P and dU, there was a fixed 8-s pause between each displacement, resulting in a regular 16-s cyclic motion. In condition dU, half of the displacements had their sign inverted semi-randomly, that is, motion was backward-then-forward instead of forward-then-backward. In condition tU, the pauses in between the displacements were varied semi-randomly between 4 and 12 s, still averaging 8 s over the 15-min experiment.

The root mean square (RMS) of acceleration was identical in all three conditions. Acceleration RMS is a main factor in predicting motion sickness (International Organization for Standardization, 1997; Lawther & Griffin, 1986; O'Hanlon & McCauley, 1974). The motion profiles of the three conditions were calculated using the ISO 2631 to lead to highly similar motion sickness vomiting incidences, which corresponds with a *Mi*sery *Sc*ale (MISC) of 10, of, respectively, 7.43, 7.52, and 7.43 for the P, uD, and uT conditions. Do note, however, that the ISO does not take into account predictability of the stimulus to calculate expected motion sickness incidence, only the physical motion over time.

MISC

To assess the participants' motion sickness, the 11-point MISC was used (Table 1; Bos, MacKinnon, & Patterson, 2005). Both before the experiment and at 1-min intervals during the 15 min, the participant indicated their score on the MISC. The scale is based on the knowledge that nausea, retching, and vomiting as a result of motion sickness are virtually always preceded by initial symptoms such as sweating, yawning, apathy, stomach awareness, and dizziness. These latter symptoms may vary between participants but are generally found to monotonically rise in severity if motion is not halted. An MISC of 6 or higher (i.e., any nausea) was taken as a cut-off point to end a condition. In the case of stopping a condition midway due to nausea, the last reported MISC

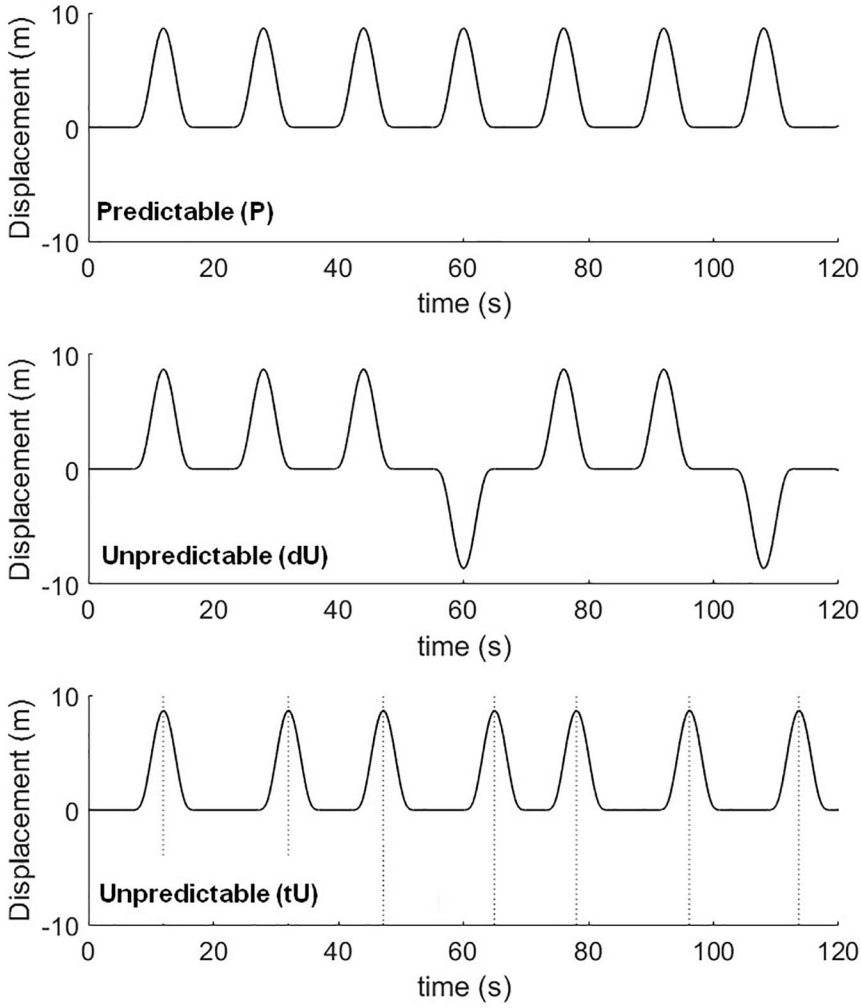

Figure 3. The first 2 min of the three conditions, here shown as displacement over time. Over the 15-min duration, all conditions use the same amount of repetitions of the basic displacement. From top to bottom the conditions shown here are predictable (P), directionally unpredictable (dU), and temporally unpredictable (tU).

score was, conservatively, assumed to remain the same for the subsequent time points.

Procedure

To get insight into the susceptibility of our subjects relative to a normal population, prior to the first condition participants filled out the motion sickness susceptibility questionnaire (MSSQ; Golding, 2006). Following this, the MISC and experimental procedural were explained. Participants were instructed to keep their eyes open during the experiment and their head in a static but comfortable position. Whenever participants felt nauseated, they were instructed to indicate this. Each condition took place on a separate day for a participant, to allow for full recovery from any residual motion sickness. Conditions were counterbalanced to prevent order effects.

Participants were informed that one condition was highly repetitive in terms of motion, whereas the other two differed either in the direction or in timing between displacements. We did not explicitly encourage participants to be cognizant

TABLE 1: 11-point MISC (Bos, Bles, & Groen, 2008)

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness, sweating, blurred vision, yawning, burping, tiredness, salivation, . . . but no nausea	Vague	2
	Little	3
	Rather	4
	Severe	5
Nausea	Slight	6
	Fairly	7
	Severe	8
	(near) Retching	9
Vomiting		10

Note. MISC = *Mi*sery *Sc*ale.

of their ability to anticipate motion. The experimenter was in contact with the participant via a two-way auditory connection over headset and could see the participant by means of a one-way video connection. During the experiment, white noise was played via a headset to mask the sound of the motors.

RESULTS

MSSQ scores of participants were on average 9.80 (SD = 5.36). This falls between the 50th and 60th percentile in terms of motion sickness susceptibility of a normal population (Golding, 2006).

After 15 min, the average illness ratings were 2.36 (SD = 1.95) for condition P, 3.58 (SD = 1.59) for condition dU, and 3.58 (SD = 1.65) for condition tU. See Figure 4 for participants' illness ratings for the three conditions over the entire 15-min period.

A repeated measures analysis of variance (ANOVA) showed a significant effect of time on motion sickness, $F(15, 195) = 12.68$, $p < .001$, partial $\eta^2 = 0.747$, and of condition on motion sickness, $F(2, 26) = 14.35$, $p < .001$, partial $\eta^2 = 0.481$. A nonparametric Friedman test on the scores at 15 min again showed a significant difference between the three conditions, $\chi^2(2) = 10.33$, $p = .006$. Subsequent Wilcoxon signed-rank tests showed that both unpredictable conditions differed from the predictable condition ($Z = -2.53$, $p = .012$ for dU and P, and $Z = -2.66$, $p = .008$ for dU and P), whereas the unpredictable conditions did not differ ($Z = 0.00$, $p > .5$).

To investigate the increase of sickness over time, we fitted regression lines to the MISC data, one for each condition, using a square root function. A square root function was a better fit when compared with a linear model, yet had the advantage of containing only one parameter preventing overfitting. See Figure 5 for the regression lines. These regression lines also significantly differed for P versus dU, $F(1, 444) = 5.0319$, $p = .025$, and for P versus tU, $F(1, 444) = 10.783$, $p = .001$, but not for dU versus tU ($p = .276$). These statistics were calculated using a dummy variable for the conditions and examining the interaction effects of the models.

Finally, we calculated regression lines for each participant and for each of the three conditions, again using a square root function. This approach had the advantage of showing interpersonal differences in the slope of increase of motion sickness over time (see Figure 6). A nonparametric Friedman test on the coefficients per condition showed a difference between the three, $\chi^2(2) = 9.57$, $p = .008$. Subsequent Wilcoxon signed-rank tests indicated that both unpredictable conditions differed from the predictable condition ($Z = -2.63$, $p = .009$ comparing dU to P, and $Z = -3.56$, $p < .001$ comparing

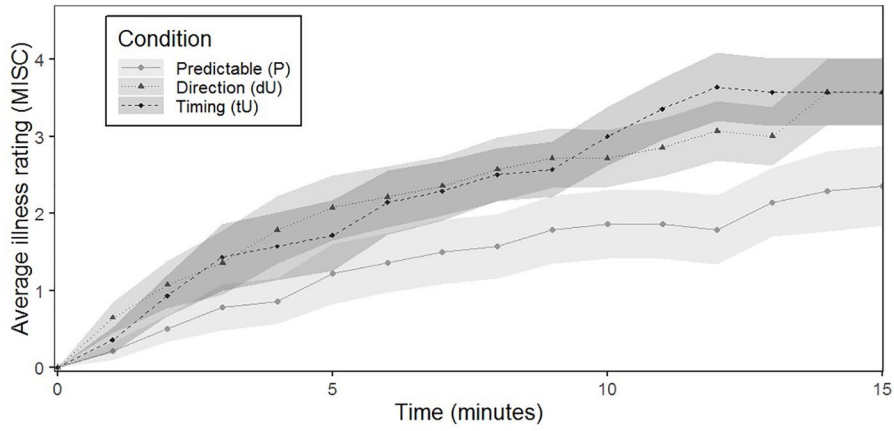

Figure 4. Average illness ratings over time for the predictable (P), the directionally unpredictable condition (dU), and the temporally unpredictable (tU) conditions. Gray bands depict standard error of the mean.

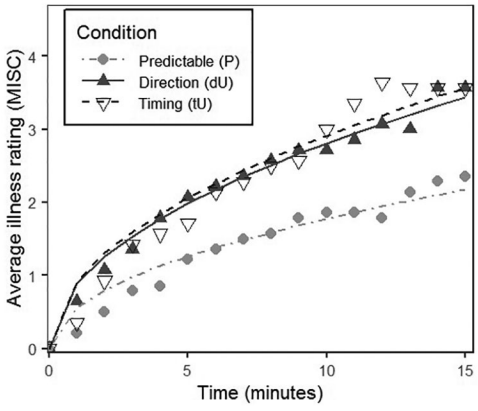

Figure 5. Regression line per condition using a square root function.

tD to P), whereas the unpredictable conditions did not significantly differ from each other ($Z = -0.43$, $p = .670$).

DISCUSSION

In this study, we compared motion sickness scores of participants in three 15-min conditions consisting of predictable motion (P), directionally unpredictable motion (dU), and temporally unpredictable (tU) motion. These three conditions consisted of motion identical in terms of displacement and were equally provocative according to ISO calculations—which do not take into account anticipation. In both unpredictable conditions participants reported significantly higher illness scores compared with the predictable condition. This confirmed our hypothesis that unpredictable motion is more provocative than predictable motion.

The differences in scores we found corresponded with 52% higher illness ratings after 15 min for the two unpredictable conditions compared with the predictable condition P. This difference between conditions also exists when considering the regression lines, indicating that illness ratings increase at a higher rate in the unpredictable conditions. Our finding, that less predictable motion is more provocative, is in line with other studies that exist in the literature (Feenstra et al., 2011; Rolnick & Lubow, 1991). The study by Rolnick and Lubow (1991) found a comparable (35%) difference between participants that were in control of a motion (and thus could anticipate it) and those that were passively moved in an identical fashion. A study by Feenstra and colleagues (2011) found that illness ratings were reduced by a factor of 2 in a condition that provided participants with additional visual information on the upcoming motion. This greater difference in scores might be the result of both conditions containing a highly erratic pattern of motion, thus having a high level of unpredictability and a potentially larger effect of the

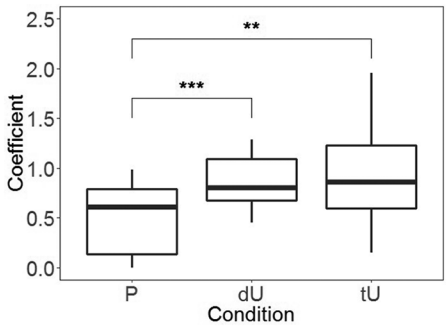

Figure 6. Boxplots showing the coefficients of the regression lines fitted for each condition and each participant. Asterisks indicate significance level (**$p < .01$, ***$p < .001$). Motion sickness increases at a higher rate for the unpredictable conditions as compared with the predictable condition.

treatment condition. Conversely, since in our study each single displacement was identical, even our unpredictable conditions still had a large degree of predictability in them. However, our design did allow us to isolate unpredictability specifically in timing and directionality. Nevertheless, it should be noted that a more erratic pattern of similarly intense motion could potentially be considerably more provocative.

Guignard and McCauley (1982) observed that certain combinations of sinusoidal vertical motion lead to more motion sickness as would be expected by adding the individual effects of single sinusoidal motions. This might be explained by the fact that a simple sinusoidal pattern is repetitive and therefore more easily allows for anticipations of motion. On the contrary, a more complex combination of sine waves appears erratic to an individual and its motion could not be anticipated by participants. Interestingly, although these authors recognize that linear addition of provocative motions does not give the full picture, they do not mention any probable causes, including anticipation.

To indicate that our three motion conditions were similar in the relevant physical regards, we calculated their expected provocativeness using the ISO standard, as also used in other studies (Griffin & Newman, 2004; Turner & Griffin, 1999). Although this Standard builds on several well-established studies on the effect of motion frequency and intensity on motion sickness, it does not take into account cognitive factors such as anticipation. The ISO standard uses the square root of the integral of the squared frequency weighted accelerations over time; that is, it considers the acceleration intensity of a motion and uses a frequency weighting centered around 0.167 Hz. However, a clear shortcoming of this standard is that it does not take into account the perspective of the individual, that is, cognitive factors such as vision and anticipation of motion. We believe our findings underline this shortcoming.

We did not find a difference between unpredictable direction (dU) and unpredictable timing (tU) in terms of motion sickness scores. What this could indicate is that the beneficiary effect of anticipation is not just a state of readiness based on timing, since that would have reflected in scores in the dU condition being equal to the predictable condition. Thus, a likely explanation is that for motion to be properly anticipated, information both on timing and on directionality should be present. This is in line with the theory that the root cause of motion sickness is a discrepancy between sensed and expected motion (Bles, Bos, de Graaf, Groen, & Wertheim, 1998; Reason & Brand, 1975). However, the current data do not give a clear insight on the underlying processes; therefore, this subject would need to be further explored.

In the literature, visual effects modulating motion sickness are often described in terms of operating through a reduction in visual-vestibular conflict (Kuiper et al., 2018; Probst et al., 1982; Turner & Griffin, 1999). However, this might not be the full picture. In addition to reducing visual-vestibular discrepancy, vision on the external world during motion (e.g., as a car passenger) can improve anticipation of upcoming motion and might therefore be even more beneficial in reducing motion sickness than generally acknowledged.

Head tilt during motion has been shown to influence carsickness (Wada, Konno, & Fujisawa, 2012); therefore, it could have been prudent to fixate participants' heads in our experiment. In the dU condition, the directional inversion of the displacements might have led to different head tilt compared with the other two

conditions (despite the instructing participants to keep their head in a static position). However, the advantage of not having fixated the head was that this resulted in a more naturalistic situation, that is, head movement as unrestrained as would occur in a car. For the same reason, we opted to have participants have keep their eyes open, analogous to working in a car with no outside view. Another factor that might have some unforeseen influence occurred in the uT condition. Due to the random timing of this condition, it is possible that per chance some participants experienced an uneven distribution of displacements over the 15-min, for example, as a result of a series of the shortest intervals in a row. Although over the 15-min period this would be compensated with longer intervals (since the average interval was always 8 s), such an uneven exposure might have the unintended effect of influencing how motion sickness build up in participants. Note, however, that, for example, the ISO 2631-1 only assumes linear cumulative increase and would not expect increased illness due to this.

Further research on this subject could investigate how to make motion in existing modes of transport more predictable by means of external cues. For example, such information could be beneficial for a passenger of an autonomous vehicle engaged in a screen and thus lacking vision outside. Auditory or haptic information on an upcoming turn or braking maneuver could facilitate anticipation and decrease carsickness. On the contrary, rearward-facing seating in (autonomous) vehicles, as is often shown in concept cars, could limit the occupants' ability to anticipate motion and exacerbate carsickness (Griffin & Newman, 2004; Salter, Diels, Herriotts, Kanarachos, & Thake, 2019). Furthermore, if anticipation can also result from recognizing a motion will repeat, as we found in the present study, simply ensuring high consistency in driving behavior (e.g., highly consistent cornering speed and profile in city drives) might decrease carsickness occurrence. Finally, the expectation to become ill can also influence eventual motion sickness (Eden & Zuk, 1995; Williamson, Thomas, & Stern, 2004). In general, researchers could focus on a multitude of modulating factors regarding motions sickness associated with perception of the individual rather than focusing solely on the physical motion characteristics.

The findings presented in this article underline the importance of anticipation in motion sickness. Motion that is more unpredictable, and thus harder to anticipate, is found to be significantly more provocative. Although the intensity and frequency of a motion are the fundamental physical aspects that underlie motion sickness, the individual's perception and cognition should not be forgotten by researchers. Not only the intensity of the ride but also what you see or do not see coming determine whether it will be a sickening trip or a smooth ride.

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KEY POINTS

- This study investigated the effect of unpredictable motion on motion sickness.
- The conditions were predictable, unpredictable timing, and unpredictable direction.
- Unpredictable motion, both timing and direction, was found to be more provocative.
- The reason for this increase in motion sickness is thought to be decreased anticipation.
- This knowledge can be used in automated cars to reduce unpredictability and carsickness.

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