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Measurement of oscillopsia induced by vestibular Coriolis stimulation

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Abstract. We demonstrate a new method for measuring the time constant of head-movement-contingent oscillopsia (HMCO) produced by vestibular Coriolis stimulation. Subjects briskly rotated their heads around pitch or roll axes whilst seated on a platform rotating at constant velocity. This induced a cross-coupled vestibular Coriolis illusion. Simultaneous with the head movement, a visual display consisting of either a moving field of white dots on a black background or superimposed on a subject-stationary horizon, or a complete virtual room with conventional furnishings appeared. The scene's motion was driven by a simplified computer model of the Coriolis illusion. Subjects either nulled (if visual motion was against the illusory body rotation) or matched (if motion was in the same direction as the illusory motion) the sensation with the exponentially slowing scene motion, by indicating whether its decline was too fast or too slow. The model time constant was approximated using a staircase technique. Time constants comparable to that of the Coriolis vestibular ocular reflex were obtained. Time constants could be significantly reduced by adding subject-stationary visual elements. This technique for measuring oscillopsia might be used to quantify adaptation to artificial gravity environments. In principle more complex models can be used, and applied to other types of oscillopsia such as are experienced by BPPV patients or by astronauts returning to Earth.

Keywords: Oscillopsia, head-movement-contingent oscillopsia, vestibular Coriolis effect, suppression, perceptual stability

1. Introduction

The goal of this study was to develop a new psychophysical method for quantifying oscillopsia sensations induced by vestibular Coriolis stimulation. Oscillopsia is clinically defined as a perceptual disturbance in which objects in the visual scene appear to move relative to an unseen world beyond. It is commonly triggered by head movements in vestibular patients [2] and is almost universal in astronauts during the first hours after return to Earth [4]. Strong oscillopsia is typically accompanied by disorientation and nausea. Currently there are no validated techniques for direct assessment of oscillopsia. The current clinical technique is to measure the resulting decrement in visual acuity (e.g. [6]). Such acuity measures do provide an index of functional visual disability but do not yield important scientific/diagnostic information relating to the underlying cause, such as the relationship between head movement and the direction and time course of resulting perceptions.

How is it that despite all the body and eye movements we make in our everyday lives, we perceive the entire visual scene around us as stable? After all, the visual correlates of self-motion relative to the world and world motion relative to the self are entirely equivalent. Apparently to resolve this inherent ambiguity we also use sensory cues from the inner ear vestibular organs and other body proprioceptors and knowledge of how

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our eyes are moving in our head to establish an absolute reference frame [10]. However, when vestibular, proprioceptive, and visual information do not fit the expected pattern, the visual scene is no longer perceived as stable [12]. A simple form of oscillopsia is easily produced by pushing on the side of your eye with your finger. Without normal information about the eye's movement, the visual world appears to move. A second simple example is the illusory visual scene rotation experienced by children, dancers and skaters when they come to a sudden stop after a period of prolonged rotation. In this case, endolymph angular momentum in the vestibular semicircular canals induces a brief 5–10 sec. sensation of illusory self motion in the opposite direction. Since the visual scene is physically motionless relative to the head, the scene is usually perceived as moving in the original direction of rotation. Usually people, recognizing the pattern of visual, vestibular and proprioceptive stimulation as discordant, are uncertain as to which reference frame is actually stationary and often report feeling "dizzy" and sometimes nauseous.

Aircraft pilots, skaters, dancers, and amusement park riders experiencing sustained rotation, experience an even more startling form of oscillopsia whenever they make a sudden head movement about an axis that does not coincide with that of the sustained rotation. Here, semicircular canal endolymph angular momentum conservation produces an unusual cross-coupled stimulus to the semicircular canals, commonly known as vestibular Coriolis stimulation [8,13]. Head movement about one axis results in unexpected apparent motion about another: rolling (ear towards shoulder) head movement during whole body rotation about a yaw axis produces predominantly an illusory pitch (nose down or up) sensation, and a pitching head movement results in the corresponding roll illusion [11]. Since the vestibular otoliths and other proprioceptors signal only the actual tilt of the head, the resulting sensation is paradoxical and provokes motion sickness whenever rotation speeds exceed 3–5 RPM.

Our interest in quantifying the oscillopsia caused by vestibular Coriolis stimulation was motivated by both operational and scientific considerations. NASA is considering the possible use of artificial gravity to reduce bone loss on very long duration space flights, which will require pre-adaptation of astronauts to vestibular Coriolis stimuli [20]. Having a straightforward method for quantifying the extent of adaptation that does not require, for example, complicated measurement and analysis of reflexive 3D eye movements could prove important, especially in view of the differences between eye movements and perception [1, 14,15]. Secondly, vestibular Coriolis stimulation provides a useful model stimulus for scientific study of sensory cue interaction, since it inherently produces semicircular canal cues that are inconsistent with those from otoliths and other proprioceptors. In this regard vestibular Coriolis oscillopsia is analogous to the very striking oscillopsia described by 0-G adapted astronauts during their first several days after return to Earth [18], about which relatively little is known because there are no reliable methods for measuring it. When these astronauts move their head during the first hours after return, they report oscillopsia strong enough to complicate emergency egress, impair their vision and trigger motion sickness. Anecdotally they describe a variety of self-motion sensations, such as linear translation in a direction opposite to head tilt [17] or sensations that their head has somehow tilted much further than it actually has. Having a practical means of quickly quantifying the dynamic relationship between head movement and apparent motion of the visual world in returning astronauts is clearly of scientific interest, and also of value to flight surgeons interested in assessing the extent of an astronaut's re-adaptation to 1-G. There have also been a few anecdotal reports of oscillopsia experienced by astronauts in flight. However, it has been impossible to determine whether this is a real phenomenon, again because a method for quantitative measurement has been lacking.

Our psychophysical method for measurement of head movement contingent oscillopsia (HMCO) is based on the principle of measuring the subject's head movement, and feeding this through an adjustable mathematical model that predicts how the visual scene should move so as to appear to the subject either (a) to be completely Earth stationary ("nulling method") or (b) to match the subject's motion with respect to the Earth ("matching method"). Matching required subjects to match the visual movement to their perceived motion. We first employed the nulling method in studies of motion after-effect [9], and more recently applied it to study the proportion of visual motion feedback needed so that virtual reality head mounted display wearers making rotational or translational head movements perceived the visual surround as stationary [12]. In both cases, the subject was asked to adjust the feedback model gain using a staircase technique until the object or scene appeared stationary. In the present case, application to assessment of vestibular Coriolis oscillopsia required us to introduce – for the first time – a dynamic model for oscillopsia into the visual feedback loop, as described further below.

2. Methods

2.1. Subjects

A total of twelve subjects (six males, six females, age 21–52 yrs) participated in this study. All had normal or corrected-to-normal vision and reported no history of vestibular or balance problems. If they wore glasses, they continued to wear them throughout the experiment. All subjects were briefed before participating and signed a consent form. Subjects were paid $10 per session. Subjects were told that the experiment could be safely halted within a few seconds without penalty should they begin to feel ill or wish to discontinue participation for any reason. This study was approved by the York University Research Ethics Board. Not all subjects completed all the conditions.

2.2. Equipment

2.2.1. Rotating platform

A rotating platform, approximately 100 cm in diameter, was constructed to induce the vestibular Coriolis stimuli (Fig. 1a). A padded bucket seat (Evo2 racing seat, Sparco Inc. Irvine, CA was mounted on the platform to secure the participant firmly in place during the experiment. The range of the platform angular velocity servo was between approximately ten and one hundred degrees per second. The platform was shrouded in a heavy, black light-proof cloth so that participants had no visual cues outside the platform that they could use to determine either their rate of rotation or their position.

The experimenter was able to observe the subject on a monitor by utilizing a wireless, night-vision camera mounted on the platform inside the shroud (for typical views see Fig. 1b). This allowed the experimenter to ensure that subjects were performing the correct actions and to watch for signs of illness or discomfort. A small mirror was placed behind the subject so that the experimenter could also monitor the image on the subject's display.

2.2.2. Visual display

Positioned 45 cm in front of the subject was a 30-inch color LCD display (Cinema HD, Apple Computer Inc., Cupertino, CA) that was used to present the computer generated moving visual scenes described below. This display was viewed through a circular aperture of 39° visual angle. The pixel response time was 16 ms, the contrast ratio was 700:1 and the pixel pitch was 0.25 mm. The image on the display was controlled by custom software running on a personal computer (Dual AMD Opteron 252 processors, 4 GB RAM, Windows XP Professional). The dot display (see below) was a 3D array developed and displayed using Psychtoolbox and MatLab. The program randomly chose the position of each dot and put it in a 3D array, then rotated the entire array and drew a dot at each point specified by the array. The virtual reality (VR) room (see below) was developed in 3D Studio Max and was displayed using MatLab's VR Toolbox using hardware OpenGL rendering. The graphics card was a PNY Technology Quadro FX4400 PCI-Express card with 512 Mb of VRAM. It output a dual-link DVI digital signal to the display at a resolution of 2560 × 1600 pixels. Both scenes were updated at the frame rate of 60 Hz.

2.3. Head movement detection

Head movement, used to trigger the visual display (see below), was monitored using a pair of velocity transducers (Watson Rate Sensors) mounted on a headband (Fig. 1b) and oriented so they were activated by pitch or roll movement, respectively. Signals from the rate sensors were fed to the computer using a National Instruments USB-6008 12-bit DAC and used to trigger the visual scenes.

2.4. Dynamic model for the oscillopsia associated with the Coriolis Effect

The oscillopsia that is caused by head movement during whole body rotation is quite complex. See [11] for a comprehensive but still incomplete description. We chose a very simplified model of the vestibular Coriolis effect because we wished to describe it with a single parameter that we could then vary systematically. We therefore made four assumptions: (i) that the oscillopsia would be largely rotational, (ii) that the angular velocity of oscillopsia would be orthogonal to the body's axis of rotation and to the axis of head rotation, (iii) that the decline of velocity would be exponential $v = a * \exp(-t/\tau)$, where v is the perceived velocity, a is the initial velocity and τ is the time constant, that is, the time to get to 1/e (0.368) of the initial velocity, and (iv) that the initial velocity would be approximately constant between subjects. The values for 'a' and 'τ' were obtained as follows.

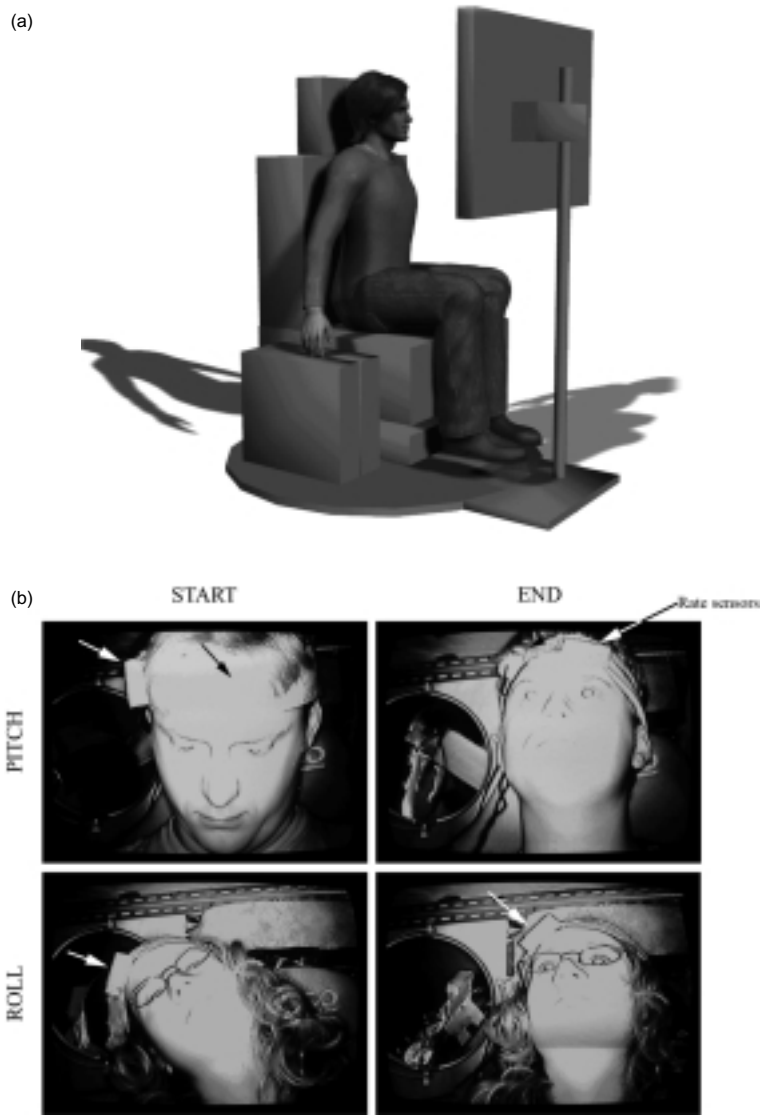

Fig. 1. A diagram of how the head-movement contingent oscillopsia was induced and measured. Subjects sat on a chair in the dark with a large screen in front of them (A). The chair was rotated around the yaw axis at constant velocity. Subjects moved their heads from start to stop orientations (B, see text for details). Note the rate sensors visible in the stills from the video taken of the subjects during the experiment.

2.5. Procedure

Each subject participated in several sessions in each of which a single axis of head movement (pitch or roll), a single type of visual display condition (dots, dots with horizon, or virtual reality simulation, see Fig. 2 and below), and a single assessment method (nulling or matching) was used. All subjects ran the dots display first and those who ran both conditions ran the VR simulation in a subsequent session. Within each session, over a series of successive trials, we used a two-alternative-forced-choice staircase method to determine the optimum time constant 'τ' for our simplified computer model. For each condition two randomly interleaved staircases were run.

During each session, subjects were seated on the platform which was gradually accelerated to 30°/sec (6 RPM clockwise), a speed high enough to produce a prominent oscillopsia, but only moderately provocative of motion sickness. The platform continued to rotate at this speed for the rest of the session. The display in front of the subject was blank before each trial. Subjects closed their eyes and positioned their heads in the 'start position' either ear-on-right-shoulder or chin-

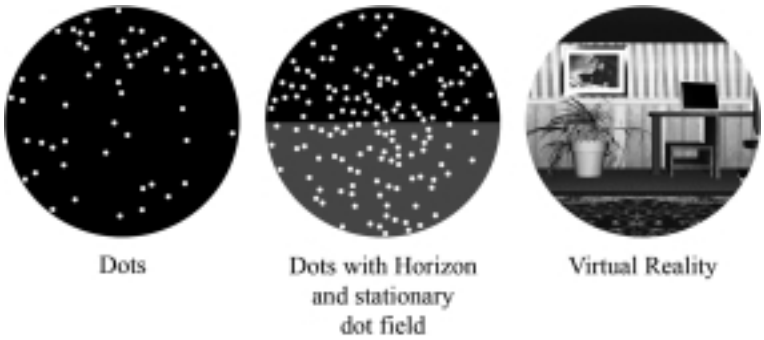

Fig. 2. The three different visual displays used. The display was masked down to a circle as shown of diameter 39° visual angle. In the 'dots' and 'virtual reality' displays the pattern moved so as simulate what would be seen if subjects actually rotated around the axis of rotation induced by the Coriolis Effect: that is, they simulated a earth-stationary scene. The 'dots with horizon and stationary dot field' consisted of the 'dots' display superimposed on a subject- (and screen-) stationary horizon and additional dot field. In this figure the dots have been enlarged to make them more visible.

on-chest (Fig. 1b), tilted approximately 30–40 degrees away from the head erect position. They then used a handheld button to "arm" the head motion detection system in preparation for a head movement. Arming was acknowledged by three beeps from the computer. When "armed", the computer awaited a signal from the rate sensors. After 30 s, on a cue from the experimenter, subjects moved their heads sharply to the upright position and simultaneously opened their eyes. The pitch or roll head movement triggered one of three types of displays (see below). When the display appeared its motion was determined by the mathematical model for vestibular Coriolis oscillopsia (see above) used by the computer. The direction of motion was either opposite to (nulling method) or in the same direction as (matching method) the pitch sensations (produced by rolling head movements) or roll sensations (produced by pitching head movement). The rotation speed of the display's motion exponentially decayed to zero with a time constant τ selected by the computer. The initial value of τ for each of the two staircases of trials was randomly chosen by the computer from a range of one to fifteen seconds. The time constant on each subsequent trial depended on the subjects' response for that particular staircase. If they responded "too fast a decline" the time constant was made longer, if they responded "too slow" the time constant was made shorter (down to a minimum of 1 s). The initial step size for this change was 5 s. When on a subsequent trial the subject switched their response (either from "too slow" to "too fast" or the reverse) the step size was reduced by half (down to a minimum of 0.5 s). After 2 responses without a response reversal, the step size was doubled (up to a maximum of 10 s). Each staircase was terminated after 4 reversals. When both staircases were complete that session was complete. Once subjects responded the screen went blank and subjects returned their heads to the particular start position for that session, armed the system, and awaited the next trial. Each experimental session lasted between 5 and 10 minutes depending on the subject.

2.6. Displays

Ten subjects viewed the dots display, twelve viewed the VR display. Seven subjects participated in both display types. The dots displays were used to null the head movement contingent oscillopsia (HMCO) motion. The virtual reality display was used to compare the effectiveness of nulling versus matching.

2.6.1. Dots without horizon

The dots were white, ten pixels in diameter and did not change shape as they moved about the screen. They were rendered by the computer on a black background and moved as if they were painted on a sphere centred on the subject's eye point with head upright, i.e., following head movement (Fig. 2a). About 100 dots were visible at any one time.

2.6.2. Dots with horizon and subject-stationary dot scene

The moving dot display (above) was superimposed on a background fixed relative to the subject. The display was divided horizontally in the middle with the bottom half blue and the upper half black (Fig. 2b). In addition, a second set of 100 randomly spaced dots were superimposed on the screen that remained stationary relative to the background horizon.

2.6.3. Virtual reality scene

The virtual reality display provided a view into a virtual room furnished with many familiar objects such as furniture, a carpet on the floor, pictures on the walls, wood paneling and wallpaper (Fig. 2c). The scene was rendered so that – like the dot display – it appeared to rotate about a point centred at the subject's eye point with head upright, i.e., following head movement. As the scene rotated, different objects successively came into view.

2.7. Reporting methods

2.7.1. Nulling method

In this condition the dots moved opposite to the subject's illusory movement. For example, if subjects felt they were moving down, the pattern would move up, maintaining the natural visual relationship when moving in a stationary world. The velocity of the dots declined exponentially. Subjects were instructed to judge the motion of the display relative to the unseen, stationary world beyond. If the dots slowed too slowly they appeared be moving more (relative to the subject) than if they were earth stationary. In this case subjects pressed a handheld button marked "TOO SLOW". If the dots slowed too quickly they tended to appear to move with the subject. In this case they pressed a button marked "TOO FAST".

2.7.2. Matching method

In this condition the pattern moved in the same direction as the subject's illusory movement. If subjects felt they were moving down, the pattern would also move in the downwards direction relative to them. This motion was not compatible with the natural visual motion when moving in a stationary world. Subjects were instructed to attend specifically to the rate of slowing of the pattern that they saw on the screen, that is, how quickly the pattern slowed, and compare what they saw with the self-motion that they felt. If the dots slowed too slowly compared with the motion they felt, they pressed a handheld button marked "TOO SLOW". If the dots slowed too quickly compared with the motion they felt, they pressed a button marked "TOO FAST".

2.8. Determining the initial velocity

There are two free parameters in the computer model of oscillopsia we were using: the time constant and the initial velocity. To obtain an estimate of this initial velocity we first chose a value that seemed a reasonable match. For a single subject we used this arbitrary value to obtain a time constant estimate. We then kept the time constant fixed at this value and used the staircases to vary the initial velocity. In this case the subject was instructed to attend only to the initial velocity and whether it appeared faster or slower than it needed to be for the dots to appear earth stationary. The resulting value of 20°/s was used as the initial velocity value for all subsequent experiments.

2.9. Questionnaire

Once participants had completed their session, they were asked about the experience. Subjects were asked to rate the amount of motion sickness they experienced in each of the directions of induced illusory motion (i.e. pitch or roll) on a scale from one to seven, one being feeling fine and seven being ready to vomit. Secondly, participants were asked about how successful they felt they had been in nulling or in matching the visual display. Finally, they were asked about the illusory motion produced by the head movement, and the extent to which it corresponded to the scene motion shown on the display. There was also a place for qualitative comments about the experience.

3. Results

After typically eight to eleven repetitions of judging whether the rate of decline of the velocity of a visual display was too fast or too slow to correspond to an earth stationary view (nulling method) or to the speed of illusory motion (matching method), the staircase criterion of 4 reversals was satisfied and the time constant was noted for each subject in each condition. Two staircases were randomly interleaved. Typical staircases are illustrated in Fig. 3. The questionnaire following each session asked whether or not they were able to match the visual display with the motion they were feeling and the majority indicated on a scale of 1 to 5 that they were able to make a satisfactory match every time (roll 4.73 ± 0.12; pitch 4.58 ± 0.18; difference not significant $t = -1.28$, $p = 0.21$, $dof = 25$).

We used a series of 2 × 2 repeated measures ANOVAs for the following tests. All values reported have been adjusted using the Greenhouse-Geisser correction. We found no significant difference in the type of display used (dots vs. VR). However, we did find a main effect of the direction of induced illusory motion (pitch vs. roll) ($F = 11.079$, $p = 0.008$, $df = (1, 10)$).

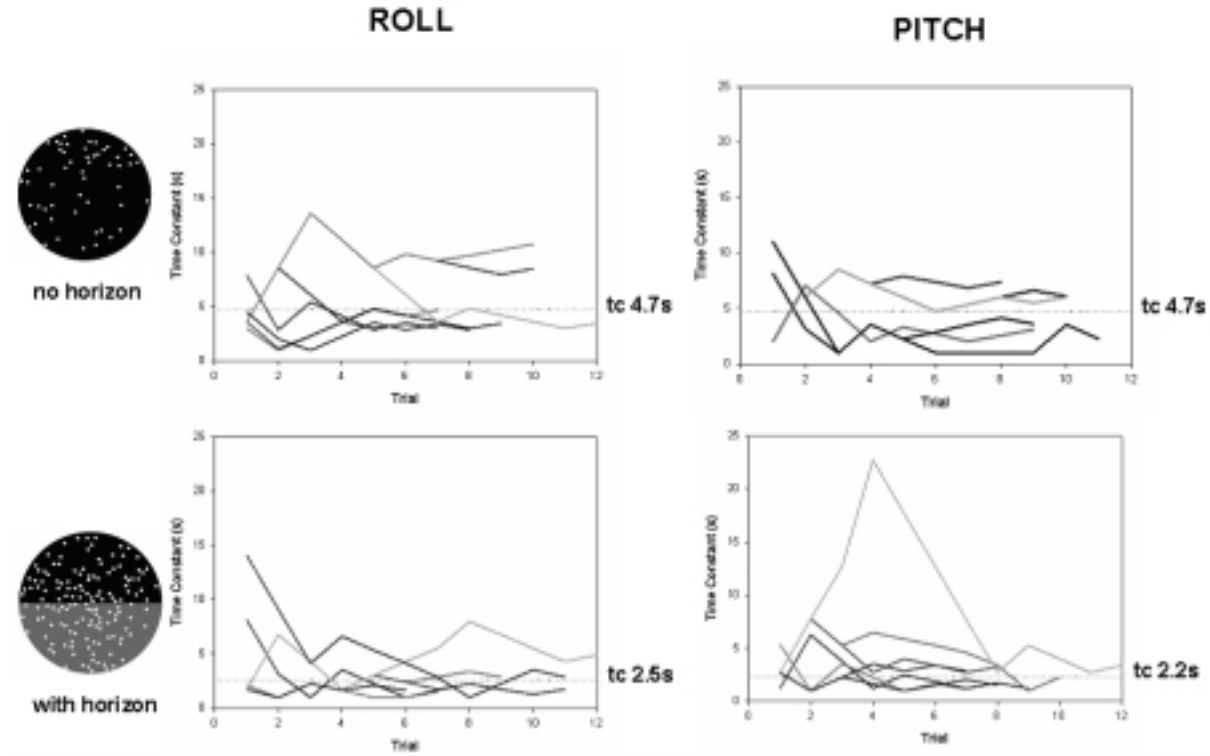

Fig. 3. Staircases were obtained for each subject for dots with and without a subject-stationary horizon for simulated roll and pitch head-movement-contingent oscillopsia Staircases were terminated after 4 reversals. Each plot shows the progression of time constants used for each trial for each subject. Each line style corresponds to the same subject in all four diagrams. Staircases typically terminated after 8–10 trials.

We also found a significant interaction effect of display type and direction of motion ($F = 8.414$, $p = .016$, $df = (1, 10)$). Because of this significant interaction, we ran another ANOVA looking just at the dots condition. Here we found that the direction of motion was not significant. However, we found a significant main effect of the presence or absence of the horizon ($F = 10.669, p = 0.022, df = (1, 5)$). Again, because of the significant interaction in the first ANOVA, we ran a third analysis that looked at just the VR condition. Here we found a significant main effect of direction ($F = 8.927$, $p = 0.015$, $df = (1, 9)$). The nulling versus matching distinction was not significant.

3.1. HMCO time constants, dot display, nulling method, with and without horizon

In the "dots without horizon" condition, the average HMCO model time constant for pitch using the nulling method was 4.7 ± 0.8 s and for roll 4.7 ± 1.0 s. These were not significantly different ($t = -0.08$; $p = 0.47$; $dof = 7$) (Fig. 4A). When the "dots with superimposed horizon" were used, the HMCO time constant dropped to 2.2 ± 0.4 s for induced illusory pitch motion and 2.5 ± 0.5 s for roll motion. The difference between roll and pitch directions was not significant ($t = -0.07$; $p = 0.475$; $dof = 5$). For both roll and pitch, there was a significant reduction in time constant as a result of superimposing the horizon and stationary dots (roll: $t = -2.42$; $p = 0.026$; $dof = 6$; pitch: $t = -3.45$; $p = 0.009$; $dof = 5$). The reduction in time constant resulting from the two different displays is illustrated in Fig. 5 which reconstructs each subject's best match display speed profile based on data from their individual trials.

3.2. HMCO time constants, nulling method, dots vs virtual reality room display

The nulling method HMCO time constants measured using the virtual room display were shorter for pitch (2.9 ± 0.4 s) than for roll (4.9 ± 0.7 s) ($t = -2.25$; $p = 0.024$; $dof = 10$) but the time constants measured in the virtual room scene were not significantly different from those measured for the dotted scene without the horizon for either pitch ($t = -0.38$; $p = 0.358$; $dof =$

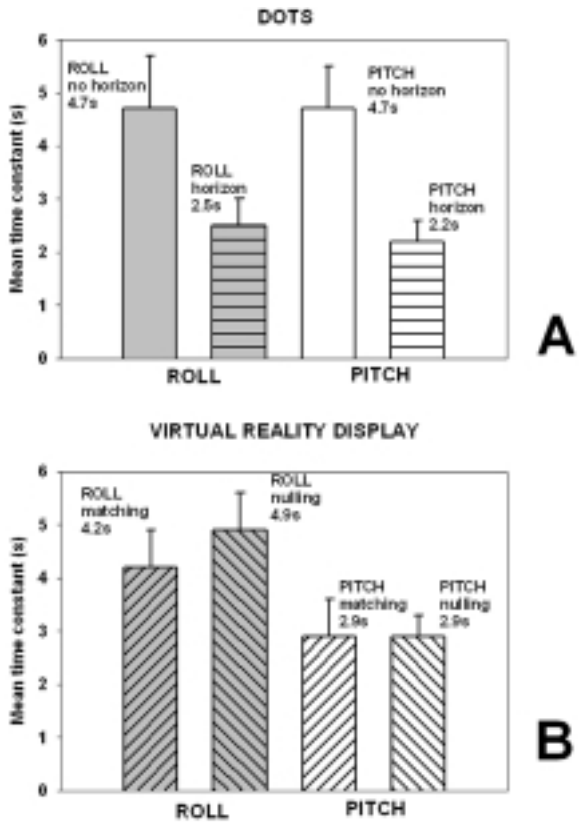

Fig. 4. Histograms comparing the time constants obtained under the tested conditions. **A** shows the time constants obtained using a nulling task with dot displays without (plain bars) and with (horizontally shaded bars) a subject stationary horizon, for roll (grey bars) and pitch (open bars) HMCO. **B** shows the HMCO time constants obtained using the virtual reality displays for roll (left two grey bars) and pitch (right two open bars) assessed using a matching task (shaded diagonals left) or a nulling task (shaded diagonals right). Also shown are standard error bars.

6) or roll ($t = 1.76$; $p = 0.076$; $dof = 4$) motion (Fig. 4B).

3.3. Comparison of matching vs. nulling method HMCO time constants, virtual reality display

Using the virtual room display we compared the matching and nulling methods. The HMCO time constants obtained using the matching task were not significantly different from those obtained with the nulling task (pitch: time constant = 2.9 ± 0.4 nulling; 2.9 ± 0.7 matching, $t = -1.13$; $p = 0.142$; $dof = 10$; roll: time constant = 4.9 ± 0.7 s nulling; 4.2 ± 0.7 s matching, $t = -0.30$; $p = 0.387$; $dof = 10$). For both tasks, the mean roll time constant (4.6 ± 0.7 s) was significantly longer than the mean pitch time constant (2.9 ± 0.4 s) ($t = -3.40$; $p = 0.004$; $dof = 9$).

3.4. Motion sickness correlation

Based on post-session questionnaire data, roll head movements were more nauseogenic (on the 1 = fine, 7 = about to vomit scale used) than pitch (pitch 2.29 ± 0.30; roll 3.16 ± 0.41; $t = -4.893$ $p = 0.0002$; $df = 11$). Because the questionnaire was administered after each session, and because the 'with' and 'without' horizon conditions were intermixed within a single session, it was not possible to compare the 'with' and 'without' horizon conditions. Dots and virtual reality displays were equally provocative (dots 2.00 ± 0.45; virtual reality 2.78 ± 0.21; $t = 0.00$, $p = 0.5$, $df = 5$). Similarly, the matching and nulling conditions could not be distinguished (pitch "with" (2.33/7 ± 0.28) vs. pitch "against" (2.36/7 ± 0.38), $t = 0.00$, $p = 1.00$, $df = 10$; roll "with" (2.98/7 ± 0.48) vs. roll "against" (3.42/7 ± 0.45), $t = -0.711$, $p = 0.493$, $df = 10$).

In their questionnaire comments, most participants reported that the roll conditions were qualitatively more compelling (and more nauseogenic) than the pitch conditions, particularly the roll "against" condition. One participant reported no tumbling/motion sensation whatsoever in either axis, stating that it felt more like a mild buzzing in the stomach. This same subject also reported no motion sickness symptoms. Another subject reported experiencing only a weak sensation of tumbling about either axis which made it difficult for them to match to the visual display.

4. Discussion

4.1. Time constants and adaptation of vestibular Coriolis responses

The HMCO time constants we found were 4–5 s, comparable to estimates of the time constant of the vestibulo-ocular reflex (VOR) elicited by vestibular Coriolis stimulation as reported by Young et al. [20]. Their study differs from the present one in that their participants were supine and were rotated much more quickly (138°/s). Their study also explored adaptation effects and found that VOR gains and time constants decreased during repeated Coriolis stimulation both within a session (typically during the first several head movements) and more gradually between sessions held on separate days, particularly when a subject stationary visual scene was present, but not across axes. Of course adaptation in the VOR may not be manifest in perceptions of rotation or oscillopsia. Certainly our

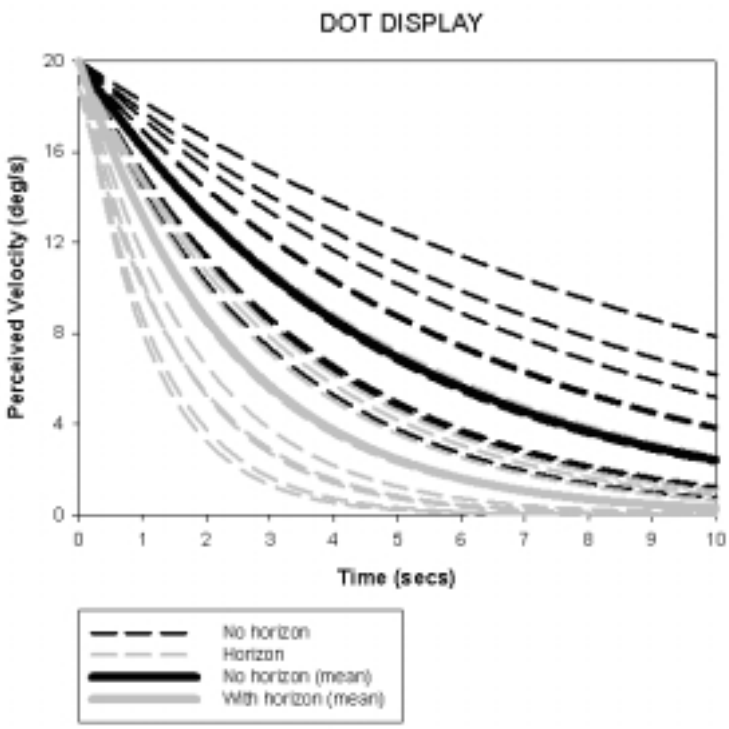

Fig. 5. Participants' perceived velocity during nulling trials reconstructed from their time constants and from a fixed initial velocity of 20 deg/s. The black lines represent the "dots without horizon" condition and the grey lines represent the "dots with subject-stationary horizon" condition. Each dashed line represents one subject in one condition; thick lines are the means for that condition.

subjects could have adapted during the first few trials of a staircase without it being apparent in our data. Some of the subjects ran as many as six sessions (up to three times in dots conditions and up to three times in the virtual reality condition) but never more than one session per day, and sessions were often separated by several weeks. A matched pairs T-Test comparing the first and last time constant results of each session showed that neither the dots ($t = -1.39$, $p = 0.18$, $df = 26$) nor the virtual reality condition ($t = 1.56$, $p = 0.13$, $df = 31$) had significantly different first and last values. We conclude that, in the short time span of this study, little or no adaptation took place.

Relatively little is known about oscillopsia adaptation. Oscillopsia in bilateral labyrinthine-defective (LD) patients is caused by the absence of the vestibular-ocular reflex (VOR). LD patients who suffer from oscillopsia tend to adapt to their condition over time. Grunfeld et al. [7] suggest that an enhanced gain of pursuit and optokinetic eye movements found in LD patients may help to stabilize images of the world on the retina during head movements. This could reduce the amount of oscillopsia experienced by these patients.

4.2. *Effects of axis of stimulation*

HMCO time constants were not significantly different for pitch and roll head movements, except in the virtual room condition, where pitch was somewhat shorter. However, the perceived visual scene motion may be different on the two axes. With visual stimuli moving in a pitch direction the scene pitching motion in the forward field may be misperceived as vertical scene translation. Previous studies in flight simulators [19] have shown that when a scene is pitched about a subject, the motion is often perceived as vertical translation rather than tilt. If the visual scene movement during pitching in a virtual room was perceived as translation, this may have made the time constants there shorter by effectively adding more of a perceived visual horizon. The subject-stationary edges of the field, which were more obvious for the virtual reality display than for the dot display, might also have contributed to the reduced time constants found in the pitch VR condition relative to the roll condition.

4.3. Reduction of HMCO time constants by subject-stationary vision

The introduction of subject-stationary visual references, that is the horizon and stationary dot field in our dotted horizon display, reduced the time constant of HMCO reported by subjects as measured by the nulling method to almost half the normal value. This is consistent with results of Brown et al. [5] who reported that subject stationary visual input enhanced the suppression of Coriolis-induced VOR. Further experiments are required to explore the exact features of the visual display necessary to create this significant time constant reduction.

4.4. Role of immersion in nulling

The nulling task involved comparing the instantaneous positions of the visual scene with the imagined real world beyond the apparatus. When the movement was ideal, the visual scene should have appeared earth stationary. We therefore felt that using as our visual stimulus a virtual reality environment with recognizable anchoring features (e.g., a floor) might make the task of seeing the room earth stationary easier and more natural. Furthermore we expected that reference points such as the horizon that could be easily associated with the unseen world beyond rather than just optic flow, might produce a more reliable estimate of the time constant involved. However there was no difference in performance between nulling (seeing the visual pattern as corresponding to the unseen world) or matching (where the task was just to observe the motion of the pattern, not to relate it to the external world) suggesting that higher level cognitive factors did not influence the ability to do the task.

4.5. HMCO and motion sickness

The Coriolis effect is known to be extremely nauseogenic [3]. Our study confirmed this, even for the modest speeds used here. Motion sickness is thought to be caused by a disagreement between the information provided by the visual system and the vestibular systems or between anticipated motion and the motion perceived [16]: both of these incongruences are found in Coriolis effects. Below decks onboard a ship, this would translate to the visual system telling the brain that the body is not moving, but the vestibular system telling the brain that it *is* moving. A well-known remedy for seasick passengers is to go up on deck and focus on the earth-stationary horizon thereby reuniting the signals from the visual and vestibular systems. The presence of a subject-stationary reference 'horizon' in our experiments means that vision had some components that said 'no motion'. It is for this reason that we expected that in the "dots" condition, the trials with the horizon and stationary dots might yield a significantly quicker decline of oscillopsia than those trials where the horizon was absent, by providing a subject-stationary reference point. Because the 'dots with horizon' and 'dots without horizon' were necessarily interleaved in the experimental design, it was not possible here to get a measure of the relative motion-sickness-inducing properties of the two motion patterns.

4.6. Conclusions

Our findings show that it is possible to quantify the time constant of decay of vestibular Coriolis oscillopsia via staircase adjustment of a parameter driving the motion of a visual display. The HMCO time constants we found were 4–5 s, comparable to estimates of the time constant of the vestibulo-ocular reflex elicited by vestibular Coriolis stimulation, at least at higher velocities (e.g. [20]). Although roll movements were more subjectively nauseogenic, time constants in pitch and roll were similar, except in the virtual room where pitch was shorter. Both matching and nulling methods proved feasible for measuring HMCO decay time constants, and using random dots or structured visual scenes seem equally effective. The addition of subject-stationary features significantly reduced the time constant of HMCO. These preliminary results are encouraging. The method could be used now to quantify perceptual adaptation to artificial gravity environments. Additional parameters could be added to the internal model to improve the correspondence between the model predictions and actual perceptions. The technique could also be used to quantify the time course and axis of other types of head movement contingent oscillopsia, such as those associated with benign paroxysmal positional vertigo, or with post-landing oscillopsia in astronauts.

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