31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Linear vection in virtual environments can be strengthened by discordant inertial input

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Abstract— **Visual and gravitoinertial sensory inputs are integrated by the central nervous system to provide a compelling and veridical sense of spatial orientation and motion. Although it's known that visual input alone can drive this perception, questions remain as to how vestibular/ proprioceptive (i.e. inertial) inputs integrate with visual input to affect this process. This was investigated further by combining sinusoidal vertical linear oscillation (5 amplitudes between 0m and ±0.8m) with two different virtual visual inputs. Visual scenes were viewed in a large field-of-view head-mounted display (HMD), which depicted an enriched, hi-res, dynamic image of the actual test chamber from the perspective of a subject seated in the linear motion device. The scene either depicted horizontal (±0.7m) or vertical (±0.8m) linear 0.2Hz sinusoidal translation. Horizontal visual motion with vertical inertial motion represents a 90° spatial shift. Vertical visual motion with vertical inertial motion whereby the highest physical point matches the lowest visual point and vice versa represents a 180° temporal shift, i.e. opposite of what one experiences in reality. Inertial-only stimulation without visual input was identified as vertical linear oscillation with accurate reports of acceleration peaks and troughs, but a slight tendency to underestimate amplitude. Visual-only (stationary) stimulation was less compelling than combined visual+inertial conditions. In visual+inertial conditions, visual input dominated the direction of perceived self-motion, however, increasing the inertial amplitude increased how compelling this non-veridical perception was. That is, perceived vertical self-motion was most compelling when inertial stimulation was maximal, despite perceiving "up" when physically "down" and vice versa. Similarly, perceived horizontal self-motion was most compelling when vertical inertial motion was at maximum amplitude. "Cross-talk" between visual and vestibular channels was suggested by reports of small vertical components of perceived self-motion combined with a dominant horizontal component. In conclusion, direction of perceived self-motion was dominated by visual motion, however, compellingness of this illusion was strengthened by increasing discordant inertial input. Thus, spatial mapping of inertial systems may be completely labile, while amplitude coding of the input intensifies the percept.**

Keywords –Self-motion perception; Vestibular; Sensorimotor integration; Presence; Immersion; Virtual reality

I. INTRODUCTION

Visual input is able to dominate self-motion perception even when inertial input is completely absent, e.g. the moving train illusion. Perception of visually-induced self-motion (SM) in the absence of actual physical motion, i.e. *vection*, has been studied extensively for over a century [1-5]. Although vection is induced by visual input, it is through the interaction with concomitant or absent inertial signals that determines perceived SM. For example, in the case of circular vection, constant velocity optokinetic stimulus rotated about the yaw axis will induce the perception of rotary SM in the opposite direction of the stimulus velocity. This phenomenon has been explained by the absence of a visual-vestibular sensory conflict, because during actual angular rotation, the semi-circular canals act similar to leaky integrators of angular velocity, so a constant velocity signal will decay in less than a minute. Unless there is visual flow to confirm the presence of motion then in the dark an individual will not detect rotation after the canal signal decays [6]. Thus, the central nervous system (CNS) firing pattern would not differ if one were viewing a constant velocity rotating visual pattern while stationary, or rotating at constant velocity relative to a stationary visual pattern. The same explanation would apply to constant velocity linear vection, when otoliths detect linear acceleration, and constant velocity will not stimulate this receptor. Thus, a constant velocity linear visual flow-field will not conflict with the expected null signal from biological inertial sensors in the absence of actual linear motion [6]. However, vection has been shown to occur in the presence of sensory discordance as well [7-12].

This study explores conditions under which linear vection can be induced by creating high levels of discordance between signals being detected by the visual and vestibular systems ("vestibular" will be used interchangeably with "inertial" or "gravitoinertial" sensation, but the latter also includes tactile and visceral mechano-receptors which cannot be easily dissociated functionally from vestibular sensation). Specifically, by exposing subjects to various levels of inertial linear acceleration while simultaneously viewing dynamic visual input that is either temporally or spatially discordant, we can assess whether visual and inertial signals integrate in a manner similar to a linearly weighted systems model or in some nonlinear manner [3, 13, 14].

II. MATERIALS AND METHOD

A. Subjects

Three of nine subjects (18-22 yrs old), who participated in an earlier study [3] returned to take part in this study for pay. The experiment was approved by the local ethics committee in accordance with the Helsinki declaration, and all subjects signed an informed consent form. None had a history of vestibular, neurological, or motor deficiencies as determined

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978-1-4244-3296-7/09/$25.00 ©2009 IEEE

by a health survey and motion sickness history questionnaire.

B. Equipment Set-up

A VR4 head-mounted display (HMD) (Virtual Research Systems, Aptos, CA) was used to display the visual scenes. The VR4 is a light, counterweighted device, designed around binocular 3.3 cm LCD displays. The field-of-view (FOV) is 60° diagonal at full overlap (36°H×48°W). The HMD optics allow for the full range of depth focus from 25 cm to infinity. Binocular disparity offset was not used. The VR4 has built-in stereo headphones, however earphones with active noise suppression were used instead.

The linear motion device was a screw-driven machine with a 15 horsepower motor, computer-controlled by Labview software (National Instruments, Austin, TX). A molded racecar driver's seat with five-point harness was attached to the platform of the linear motion device such that the seat aligned the subject's longitudinal axis with gravity. The device was programmed to oscillate at a frequency of 0.2 Hz in sinusoidal profiles with amplitudes that could be varied from ±0.1 to ±0.8 m (A, where amplitude equals half peak-to-trough distance). The corresponding peak inertial accelerations ranged from 0.16–1.26 m/s^2, according to the equation, $a = -(2\pi f)^2 A \sin(2\pi f t)$.

Visual scenes were created using digital video. The digital recorder was attached to the linear motion device and recorded the surrounding room from the same eye level perspective that a subject would view it if buckled into the racecar seat. The lowest point of travel the camera was 1.5 m above the floor and at the highest point 1.5 m below the ceiling (5 m high). The visible scene from the perspective of the seat was a 5m x 7m x 18m (HxDxW) volume of space, which was filled with an array of equipment, office furniture and boxes. The digital recorder had no magnification relative to normal vision. Two different visual scenes were recorded. The vertical linear oscillation (VLO) depicted 1.6m peak-to-trough visual VLO at frequency (f) of 0.2 Hz and amplitude of ±0.8m (A) with an accompanying soundtrack of the machine noise that the motion device made during ±0.8m/0.2Hz VLO. The velocity of optic flow this visual scene had a peak velocity of 1.0 m/s (2). The second recorded scene depicted ±0.7m of horizontal linear oscillation at 0.2 Hz, which was recorded using a horizontal track driven by the vertical linear motion device via an in-house designed pulley system. The peak velocity of this scene was 0.88 m/s in accordance with $\nu = 2\pi f A \cos(2\pi f t)$.

C. Procedure

Subjects were kept naïve of the capabilities of the vertical linear motion device by escorting them to the device while blindfolded. They were allowed to view the test chamber briefly after being strapped-in, which prevented them from seeing the vertical rails of the motion device behind them. When the blindfold was removed they could view the room in front of them from the same vantage point that the visual scenes were recorded. Subjects were tested in the two visual conditions at five amplitudes of inertial motion in a randomized order. The five inertial amplitudes of 0.2Hz sinusoidal motion were 0 (stationary), ±0.1, ±0.2, ±0.4, and ±0.8m peak to trough displacement. The visual scene was head-fixed in all conditions, so the visually depicted room horizon was parallel to the inter-ocular axis at all times. The dubbed auditory signal, corresponding to machine noise during ±0.8m/0.2Hz VLO, was the same for all conditions which subjects listened to in noise dampening headphones. The conditions were as follows:

HOR – view 1.4m left-right sinusoidal translation while being exposed to each of five inertial levels of VLO. The peak and trough of inertial motion was synchronized with the left and right visual extremes.

VERT – view 1.6m peak-to-trough vertical sinusoidal translation while being exposed to each of five inertial levels of VLO. Peak and trough of inertial motion was phase shifted to synchronize with trough and peak of visual motion.

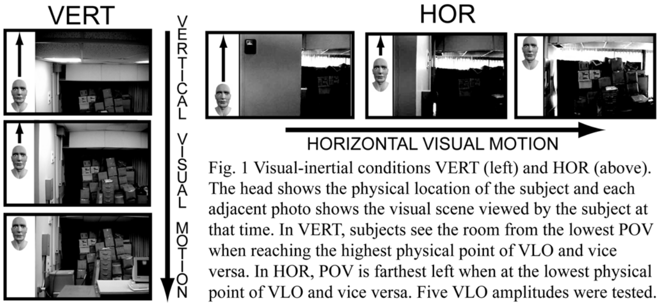

Fig. 1 Visual-inertial conditions VERT (left) and HOR (above). The head shows the physical location of the subject and each adjacent photo shows the visual scene viewed by the subject at that time. In VERT, subjects see the room from the lowest POV when reaching the highest physical point of VLO and vice versa. In HOR, POV is farthest left when at the lowest physical point of VLO and vice versa. Five VLO amplitudes were tested.

Sessions were run on three separate days with at least 48 hours separating test days. Each session involved one visual condition at five inertial level of VLO in randomized order. Each trial lasted three minutes with a five minute break between trials. Machine noise and vibration was minimized by placing dense foam between the back, buttocks and racecar seat. By playing the auditory recording from the ±0.8m/0.2Hz motion condition at high volume, motor noise was drowned out equally in all conditions.

Three dependent measures during each three-minute trial were collected: perceived SM amplitude, *compellingness* of SM, and path of SM. Subjects reported perceived peak-to-trough or left-to-right amplitude in standard metric units, i.e. feet or meters whichever was most familiar to the subject. Subjects were instructed to scale their judgments in each condition relative the one another. A continuous relative rating scale was reported to determine level of compellingness of perceived SM using numbers from 0–5.This was included as an independent measure of perceived amplitude of SM. It was intended to provide a second measure of visual-vestibular interaction that was not dependent on the ability to judge metric distances, which may include inherent perceptual biases. This scale was dependent on the ability to judge an internal state on a normalized scale. Subjects were familiarized with this scale in the earlier study that they participated in. The inter-subject reliability of this metric was verified using a Kendall coefficient of concordance in a previous study [3]. In this scale, zero equates to no compelling SM, while greater than zero suggests SM velocity and/or displacement perception. For example, the well-known perception of SM one experiences when standing still on a train platform when the train slowly pulls away illustrates how compelling SM in the absence of real motion can be very convincing but dissipate quickly. SM accompanied by pressure cues, wind cues, and visceral cues would be indicative of a heightened compellingness, but are not necessary to experience SM. The highest level of compelling SM should include both stable, persistent velocity and displacement with recognizable spatial components. The spatial components described by path and direction of SM were the third dependent measure subjects reported. Finally, although each trial lasted only 3 minutes with rests in between, symptoms of motion (cyber) sickness were monitored and subjects were free to stop at any time. Repeated-measures general linear models were used to test for effects of inertial amplitude, visual condition, and interactions. Mauchley's test of sphericity determined Greenhouse-Geisser epsilon adjustments to the degrees of freedom where necessary. Significance was set at $p<0.05$.

III. RESULTS

A. Horizontal visual motion

All subjects reported the perception of compelling horizontal SM in synchrony with visual direction rather than actual inertial direction. As amplitude of inertial VLO was increased, the amplitude of perceived horizontal linear SM showed an increasing trend ($p<0.10$, n.s.) while increases in the compellingness of perceived horizontal SM were significant ($F_{4,8}=6.48$, $p=0.013$) (see Table I). Of the 15 trials that were run, only at peak inertial amplitude of vertical oscillation was a small component of vertical SM reported. One subject reported diagonal motion with 2m of left-right motion and 0.5m of up-down motion, however, up-down was opposite in direction from inertial motion. Another subject reported a 10cm dip or rise at extremes of left-right motion, but the remainder of the cycle was a flat horizontal path.

B. Vertical visual motion

All subjects reported perception of compelling vertical SM in synchrony with visual phase of motion rather than actual inertial phase. As amplitude of inertial VLO was increased, a significant increase ($F_{4,8}=6.08$, $p=0.015$) in the amplitude of perceived vertical linear SM was found (Table I). Reports of how compelling the perceived SM was also increase significantly with inertial amplitude ($F_{4,8}=17.2$, $p<0.001$).

C. Other subjective reports

Subjects often reported visceral, tactile, and/or wind cues that matched the perceived direction of SM, despite the fact that these were not concordant with the inertial motion. When vertical inertial and visual input were 180° out-of-phase, but the axes of motion were aligned in VERT, there were reports of an "elevator" feeling as well as mild epigastric awareness and slight dizziness.

D. Comparisons with previous results

Comparisons can be made with conditions run with the same subjects in a previous study [3]. First, the counterpart of temporally phase-shifted vertical visual+inertial condition (VERT) is a synchronized vertical visual+ inertial condition (HiV) in the previous study. The only difference between conditions was a 180° phase-shift in visual motion relative to inertial motion. No difference in compellingness or amplitude was found between visual conditions, despite large differences in visual-inertial concordance ($p>0.40$, n.s.).

A second comparison can be made between VERT and the low-amplitude temporally phase-shifted visual condition (PSLo) from the previous study [3]. Both VERT and PSLo exposed subjects to temporally discordant vertical visual+ inertial motion, with the only difference being a smaller sinusoidal amplitude of visual motion in PSLo (±0.1m) compared to VERT (±0.8m). Results revealed a marginally significant difference in amplitude of perceived SM ($F_{1,2}=16.6$, $p=0.055$), however in trials with higher amplitudes of VLO, the direction of SM perception was more ambiguous for subjects. Instead, it tended to become entrained with the inertial motion, rather than visual phase, or phase of visual motion could not be accurately reported, or when asked to indicate SM with a handheld joystick, subjects manually indicated one direction but verbally reported the opposite direction.

TABLE I

Visual Cond.	INERTIAL AMPLITUDE 0 m	0.1 m	0.2 m	0.4 m	0.8 m
LINEAR VECTION AMPLITUDE					
HOR	0.76(0.4)	0.77(0.2)	1.2(0.5)	1.1(0.4)	1.8(0.3)
VERT	0.56(0.3)	0.67(0.1)	0.94(0.2)	1.7(0.2)	2.0(0.3)
LINEAR VECTION COMPELLINGNESS					
HOR	0.77(0.6)	3.0(1.0)	3.3(0.2)	4.0(0.2)	4.5(0.3)
VERT	0.50(0.3)	2.0(0.3)	3.5(1.0)	4.3(0.4)	4.8(0.2)

Linear Vection Amplitudes are reported in meters. Compellingness is a unitless scale from 0-5. Standard error is reported in parentheses.

IV. DISCUSSION

During sinusoidal VLO and large FOV virtual visual linear oscillation, subjects perceived compelling SM concordant with visual input even if direction of visual linear motion was orthogonal to the linear inertial motion or if phase of visual motion was opposite of inertial motion. Furthermore, in both visual conditions by increasing amplitude of inertial vertical oscillation amplitude and compellingness of non-veridical perceived SM significantly increased. This occurred despite amplitude of visual oscillation being constant.

That linear vection can occur in the presence of large visual and inertial discordance has been experimentally shown many times [1, 4, 8-11, 13]. By using large FOV visually enriched virtual environments with a full range of depth focus, linear vection is successfully induced even in the absence of any inertial motion. However, the results showed that by adding increasing amplitudes of inertial acceleration SM perception consistent with the visual stimulus became more convincing, despite this causing a commensurate level of visual and inertial sensory discordance. A linearly summating model might suggest a complete cancellation of SM perception in VERT, whereas in the HOR condition we might expect an increasingly diagonal left-up and right-down path of motion. If however the CNS engages a sensory switching or weighting strategy [1, 14] or reciprocal inhibition [7, 15] then one wouldn't expect compellingness of SM perception to increase with sensory discordance.

One possible reason that compellingness of non-veridical SM increased with increasing levels of inconsistent inertial cues may be due to increasing levels of machine vibration from the screw-driven linear sled [15]. Although transmission of machine vibration was minimized using velocity-sensitive foam padding and earphones with active noise reduction, detection of machine noise by the vestibular organs and tactile mechanoreceptors cannot be discounted. Unlike the wind and pressure cues from inertial motion, these signal are omni-directional and the CNS may associate them with salient inputs in present in the sensory array.

Finally, the 0.2Hz frequency of sinusoidal oscillation was specifically chosen because it has been identified as a cut-off frequency where visual and vestibular systems transition in dominance [16-18]. This means that at the driving frequency the visual input may still be dominating, and an increase to a higher frequency may result in suppression of visual input in favor of the inertial input.

V. CONCLUSIONS

Prism adaptation studies over the last century have informed us that visual, vestibular, and motor remapping can occur to such a degree that complete inversion of the visual world can be remapped in the CNS such that behavior is virtually normal again in just a few days [19], while patient studies revealed that certain brain injuries result in large scale spatial transformation of visuomotor or visual-vestibular maps [20]. In fact, using the lability of these spatial maps, researchers have been able to ameliorate hemi-neglect symptoms by laterally shifting the visual field with prisms [21]. Another stroke induced phenomenon causes contraversive pushing syndrome is believed to be due to misalignment of perceived subjective visual vertical and subjective postural vertical [22]. It's possible that in a dynamic interactive VE, a realignment of the dissociated bodily, visual, and inertial maps can be quickly effected. Current findings suggests that these spatial maps can be very effectively altered using dynamical VE to induce highly compelling spatial reorganization. Similar dynamic VE experimental set-ups show that non-veridical dynamic perceptions induce automatic motor responses in the upper-extremities [23], which can likely be applied to rehabilitation in the safe and controllable experimental environments that VE technology affords.

ACKNOWLEDGMENT

Special thanks to Drs. Paul DiZio and Jim Lackner for support and to Dr. Simone Bortolami, who designed the vertical linear motion device.

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