Perceptual Tolerance to Motion-To-Photon Latency with Head Movement in Virtual Reality

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***Abstract*—Since Motion-To-Photon (MTP) latency is inevitable and can be perceived in virtual reality, quantifying perception of MTP latency becomes necessary. In this paper, we investigate perceptual tolerance to MTP latency, including perception threshold of the latency and user acceptance of delays above the threshold. It is affected by different head motion events, such as Motion-Static-Alternate (MSA, i.e., an acceleration or deceleration in one direction) and Motion-To-Reverse (MTR, i.e., a movement reverses direction). In each motion event, rotation angle and angular velocity also influence perception of MTP latency. Experimental results show that subjects are more intolerant of MTP latency in MTR than MSA. The latency perception threshold is about 23 ms when subjects turn their heads at the maximum speed of human limits. When the angular velocity decreases, the perception threshold increases. The maximum threshold is $\sim$41 ms at 20 $^\circ/s$ in this study. Inversely proportional models are established to describe the relationship between threshold and angular velocity. Besides, MTP latency over the threshold is harder to be accepted with the rotation angle decreasing or the angular velocity increasing.**

***Index Terms*—Latency, perception threshold, user acceptance, head movement, virtual reality**

I. Introduction

Virtual reality (VR) has been becoming increasingly popular due to realism, ease of interaction, and richness of imagination. However, Motion-To-Photon (MTP) latency is an inevitable shortcoming. It's defined as the lapse between a human movement and its equivalent change to the new FOV shown to the eyes [1]. MTP latency will cause motion feedback lag that generates the mismatch of motion signals between the vestibular and visual channels. As a user turns his head, the vestibular system immediately produces motion perception. But the visual system lags behind because the corresponding viewport will be rendered for eyes later. The higher MTP latency, the easier it is to detect the mismatch by various manifestations, such as content lagging behind head motion, image slip [2] and instability of the virtual environment [3]. Indeed, high MTP latency can lead to oscillopsia, degraded vision, and motion sickness [3], as well reduce task performance [4][5], even sense of presence [6]. The perception studies are needed to define low MTP latency and its influencing factors, which will benefit an acceptable system design and evaluation.

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In previous latency perception threshold studies, Allison et al. [3] observed perceptual sensitivity for latency threshold when subjects yawed their heads 45° at various angular velocities. The results showed that 50% thresholds increased from 180 to 320 ms with average speeds decreased from 90 to $22.5^\circ/s$. Adelstein et al. [2] used a forced-choice method. The average Point of Subjective Equality (PSE) and Just Noticeable Difference (JND) for latency discrimination were reported as 58.8 and 13.6 ms. These studies indicated that MTP latency perception threshold depended on the velocity of head movement [3][7]-[9] and the trait of target subjects [10], rather than subjective assessment method [7], FOV [7], scene complexity [8] and scene realism [9]. Previous studies only focused on the latency perception threshold without describing user acceptance of MTP latency over the threshold. Only head rotation angular speed was set as main variable of head movement. However, the impacts of head movement change in angle and direction on latency perception are not yet clear.

In VR, it should be prudent to control subjects' movements. Because subjects are usually allowed to move freely for fully experiencing. In [7], subjects sat on a rotating chair and moved passively with the chair's rotation. But subjects might have different feelings about latency with passive and active motions. In [2][3][10], subjects could turn their heads freely but purposefully at a specific speed by metronome signals as audio cues. However, there was little description for results of using audio cues to control head movement. Furthermore, compared with auditory sensation, vision is generally considered to be better at processing motion and spatial information, yet worse in temporal perception [11]. This implies that people can better handle self-motion displacements and speeds by visual cues, but react more quickly by audio cues.

This paper studied the effect of head movements on both perception threshold of MTP latency and user acceptance of latency above the threshold. First, a series of experiments were conducted for revealing the effect of head motion, rotation angle and angular velocity on tolerance to MTP latency. Then, inversely proportional models were established to describe the relationship between threshold and angular velocity. Moreover, visual cues were introduced instead of audio cues. All subjects' head movements were recorded to analyze their performance in the motion task.

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II. Methods

There was an MTP latency in the virtual environment. A subject was required to watch a 360 degree video under the specified head movement task, and then give a subjective score for the MTP latency. Once the subject viewed the 360 degree video, head tracking data (i.e., position and orientation), timestamps and video information would be recorded into a log file.

A. MTP Latency

The inherent MTP latency of the experimental platform is about 28.5 ms, measured by Steed's [15] method. We added an added latency model by a ring buffer. The amount of added latency depended on the size of buffer and the frequency of head data tracker. Head data was collected at 120 Hz and stored in the buffer. Actually, one head data was respectively multiplied by two offsets as the left and right eye data for rendering viewports. We defined the time required for the left and right eye data as the unit time. Calculated by the log file, the unit time was ~11 ms. Assuming the length of the ring buffer was N, then added latency was about 11*(N - 1)/2 ms. In this experiment, seven added latencies were set at 0, 11, 22, 33, 44, 66, and 88 ms.

B. Head Movement Task

High MTP latency could cause a mismatch of motion perception between the vestibular and the visual system. We hypothesize that perceptual sensitivity of MTP latency can be affected by head movements, including motion event, angle, angular velocity. There were two motion events of Motion-Static-Alternate (MSA) and Motion-To-Reverse (MTR), two angles of 40 and 80°, and five velocities of 20, 40, 60, 80, and Inf $^\circ/s$.

Two motion events: When keeping still or moving at a constant speed, subjects won't notice the mismatch no matter how high MTP latency is. The mismatch can be obviously exposed when a sudden head movement occurs, such as acceleration, deceleration, and direction change. Two extreme abrupt motion events, Motion-Static-Alternate (MSA) and Motion-To-Reverse (MTR), were designed for experiment. MSA was defined as an abrupt start (acceleration) or stop (deceleration) of the motion in one direction. There was no difference in the effects of acceleration and deceleration on MTP latency perception by our preliminary experiments. MTR was defined as an instantaneous motion in the opposite direction. For example, a left-to-right head motion suddenly changed into right-to-left.

Two angles: In MSA, both the beginning and end of turning are stimuli. To eliminate interference from adjacent stimuli, subjects should spend enough time on a constant speed rotation (i.e. no stimulus) before stop. By trials, head rotation angles were set to 40 and 80°, which were suitable for humans. Taking an example of MSA, a subject stayed still (2 s) at position A, then smoothly yawed head 40° to position B, stayed next 2 s at B and finally went back to A. For MTR, the only change was no 2 s stay at B. In other words, as the subject arrived at B and then returned to A at once.

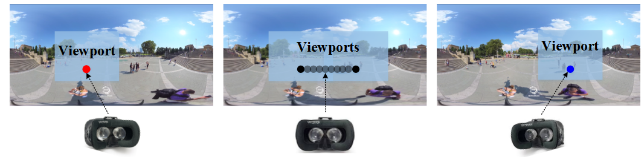


Fig. 1. Three color dots as visual cues in viewports (blue blocks).

Five angular velocities: Subjects were required to turn their heads at a specific angular velocity. Usually, people can track the moving object at the speed within 1~100 $^\circ/s$. For both MSA and MTR, there were four angular velocities (20, 40, 60, and 80 $^\circ/s$). Besides, MSA had a special angular velocity (Inf $^\circ/s$), but MTR did not. Inf $^\circ/s$ was the maximum head rotation speed that a subject could naturally achieve. The process was as follows, a subject was still (2 s) at position A, and then turned head as quickly as possible to position B (i.e. the velocity is infinite), stopped directly and stayed 2 s. This is inspired by saccades, that is, s a gaze point shifts from A to B. Since a new object need to be stared at long enough for forming the clear image on the retina. When the head arrived at B, should not move in the opposite direction immediately. Thus, we did not set Inf $^\circ/s$ for MTR. In short, there were five angular velocities (20, 40, 60, 80, and Inf $^\circ/s$) in MSA, but four in MTR without Inf $^\circ/s$.

C. Cues for Guiding Head Movement

Magnocellular cells (M-cells) which are located at periphery of the retina, are sensitive to moving stimuli [12]. Inspired by this, three color dots as visual cues were placed 10° below the center of video as shown in Fig. 1. Red and blue dots were set at fixed positions to mark the beginning and end of the movement. And a moving black dot guided subjects to turn their heads. Indeed, subjects could follow visual cues well without much attention. Most attentions were focused on the central area of viewport when there was an MTP latency.

D. Procedure

We employed the single stimulus method with a five-level rating scale : -1 (imperceptible), 0 (uncertain), 1 (perceptible, but not annoying), 2 (annoying), 3 (very annoying). This rating scale can be used to calculate MTP latency perception threshold just like Yes/No response, but also measure user acceptance of MTP latency above the threshold.

There were a total of 2 x 5 + 2 x 4 = 18 movement tasks. In each task, there were 28 trials with four 360 degree videos and seven added latencies. For each trial, it took a subject 5~14 s to experience and next 5 s to give the opinion score. Subsequently, the next trial started until all 28 trials were completed. A subject would spend ~160 minutes completing all trials. In fact, subjects usually feel nausea and uncomfortable beyond 20 minutes in VR experience. Hence, each subject's experiment was divided into three sessions on different days. In the beginning of first session, we introduced the concept and process of the experiment for subjects. Then, they were kept training until their own evaluation criteria were

TABLE I

AVERAGE ACTUAL ANGULAR VELOCITIES ($^\circ/s$)

Reference Velocity ($^\circ/s$)	20	40	60	80	Inf
Mean	22.8	52.0	78.1	103.3	214.0
SD	1.8	4.9	7.9	10.7	63.4

established. Before starting the other two sessions, subjects were tested and trained to form the same criteria as previous. These training processes would take another $\sim$60 minutes. Each session lasted 60$\sim$100 minutes with an enforced 20 minute break per 20 minutes. Before and after each 20 minute test, subjects were required to fill out Simulator Sickness Questionnaires (SSQs) [18] for quantifying their simulator sickness. The order of movement tasks for each session was randomized, and the order of trials for each task was also random. All subjects were tested in different orders.

III. MATERIALS

A. Video Content

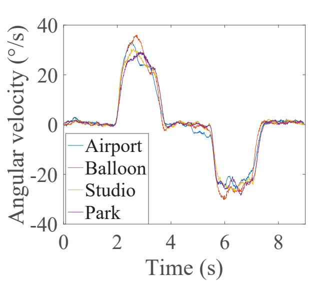
Five 4k 360 degree videos with 30 fps were downloaded from YouTube [13], including 'Airport', 'Balloons', 'Lions', 'Studio', and 'Park'. Cameras that shot 'Airport' and 'Balloons' moved slowly in direction of the depth of field. The other videos were shot by static cameras. 'Studio' was an indoor scene, and the others were outdoor. 'Lions' was used in training phases, and the others were used in testing phases.

B. Subjects

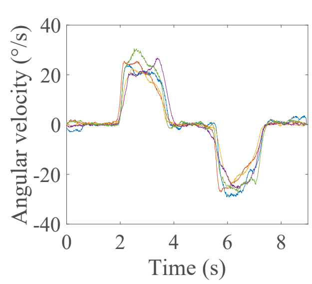
As at least 15 non-expert subjects should be employed [16], 19 non-experts (11 males, mean age 23 years, range from 20 to 27 years) with normal vision or corrected to normal vision participated in the study. None of them had been involved in any latency perception experiments. Subjects who were prone to eyes fatigue, carsickness or seasickness or simulator sickness were excluded.

C. Apparatus

Based on the HTC Vive system [14], an experimental platform was established by employing the HTC Vive Cinema software [17]. The HTC Vive head mounted display (HMD) had resolution 2160 x 1200 with a 110° FOV and 90 Hz refresh rate. The rendered images were transmitted from a personal computer (PC) to the HMD via an HDMI cable. The PC was configured with an NVIDIA GTX 1070 GPU, an i7-6700 CPU, 8 Gigabytes of RAM.

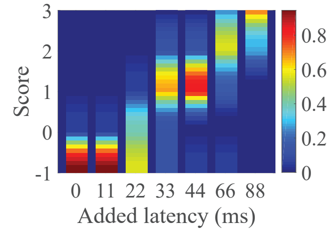


(a) Velocities of No.15 subject

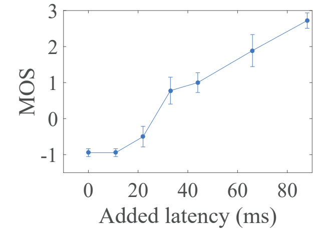


(b) Velocities of five subjects

Fig. 2. Actual angular velocities of subjects under the head rotation of 40° at 20$^\circ/s$ in Motion-Static-Alternate. (a) Each color represents a video. (b) Each color corresponds to a subject.



(a) The probability graphic



(b) MOS with 95% CI

Fig. 3. The subjects rotated 40° with 60$^\circ/s$ in Motion-Static-Alternate. The video was "Balloons". The closer the color is to red, the higher the probability.

IV. EXPERIMENTAL RESULTS

We deployed the screening method [16] and remained 18 valid subjects. The following content discusses subjects' performance of head movement tasks, perceptual features of MTP latency at and above the threshold, and simulator sickness.

A. Angles and Angular Velocities of Head Rotation

Actual angles and angular velocities of yaw rotation were obtained by processing data of head position and orientation. For each subject, the actual angle was obtained by averaging measured angles of all trials. On 40° condition, the mean of actual angles of all subjects is 42.8° with a Standard Deviation (SD) of 3.7°. At 80°, the mean is 79.3° with the SD of 4.0°. The result indicates that visual cues can help subjects yaw their heads at a particular angle with little error.

Similarly, means and SDs of the actual angular velocities were calculated (Table I). Five distinct actual velocities are presented, yet greater than the reference velocities. A large SD occurs when subjects can freely yaw their heads at their own maximum velocity (Inf $^\circ/s$), while SDs are small for other strictly controlled velocities. These findings suggest that visual cues can weaken individual differences in the head movement task. Intuitively, Fig. 2 shows temporal consistency of angular velocity within a subject and among subjects. Consequently, visual cues help to effectively control head movement, which ensure subjects have the same head motion at the same time.

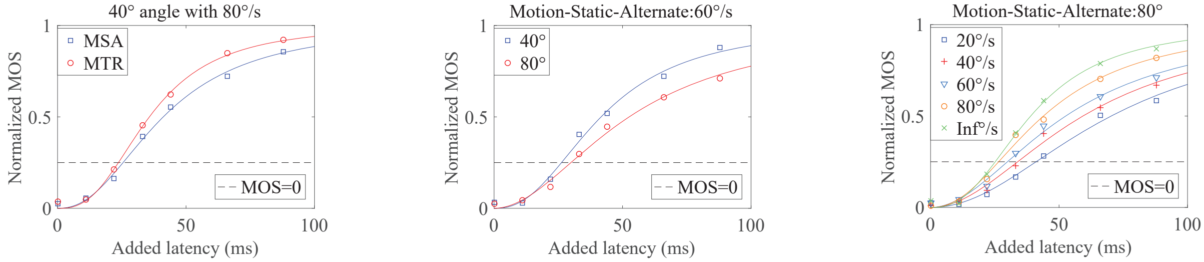
B. Perceptual Threshold of MTP Latency

Since scores of all subjects are centrally distributed at each added latency as shown in Fig. 3 (a), the mean opinion scores (MOS) with 95% confidence intervals (CI) are used to report central tendencies. To verify the effects of video

TABLE II

THRESHOLDS (MS) OF ADDED MTP LATENCY UNDER VARIOUS MOTION EVENTS, ANGLES AND VELOCITIES

Velocity ($^\circ/s$)	Event-Angle(°)			
	MSA-40	MSA-80	MTR-40	MTR-80
20	37.35	40.70	30.89	31.24
40	32.27	33.90	26.84	27.86
60	26.18	29.94	25.95	24.78
80	25.65	26.39	23.70	23.00
Inf	22.71	25.44	-	-



(a) Motion-Static-Alternate vs Motion-To-Reverse (b) 40° vs 80° (c) Five angular velocities

Fig. 4. Normalized MOS versus added latency: points are measured MOS, curves are fitted logistic models.

content and movement task on MTP latency perception, all MOS were divided into 72 groups. Each group had seven MOS corresponding to seven added latencies. Since Lilliefors tests for normality suggested that all sample sets were normal data at 95% confidence level. We employed Analysis of Variance (ANOVA) tests. Motion event (all $p < 0.05$), angle (all $p < 0.05$) and angular velocity (all $p < 0.05$) all had significant impacts on MOS of MTP latency. However, there was no significant difference among video contents (all $p > 0.05$). Similar to previous research [8][9], scene complexity and camera motion did not affect latency threshold. Thus, content difference is not considered in the following.

In Fig. 3 (b), MOS values change slowly at first and then increase rapidly with added latency. Finally, with the greater latency, the smaller acceptance difference can be perceived. This implies the mean opinion scores of added latency can be approximated by a fitting logistic function. First, the min-max normalization is used to normalize MOS. Second, the least squares estimation is used to determine best-fit logistic functions as shown in Fig. 4.

In five-level rating scale, a score less than or equal to 0 means that subjects won't notice latency. Thus, the perception threshold is set as an added latency whose MOS equals to 0. The Table II lists all thresholds. The maximum is 40.70 ms at a 80° head rotation angle with $20°/s$ in Motion-Static-Alternate. And the minimum is 22.71 ms at 40° with Inf $°/s$ in MSA.

Significance analysis reveals the effect of motion event, angle, and angular velocity on the perceptual threshold. Lilliefors tests and homogeneity of variance tests manifest that thresholds are normal data at 95% confidence level (all $p > 0.05$) with homogeneity of variance. Then, analysis of variance (ANOVA) tests suggest that the threshold is affected by motion event ($p = 0.0022 < 0.05$). Apparently, subjects can notice MTP latency more easily in Motion-To-Reverse than Motion-Static-Alternate as shown in Fig. 5. This indicates that the direction change increases perceptual sensitivity to MTP latency.

But angle could affect the threshold in MSA ($p = 0.0118 < 0.05$), but did not in MTR ($p = 0.8210 > 0.05$). In MSA, the start of head movement is the first stimulus, the end of the movement is the second. Only when the rotation angle is large enough, the two stimuli will not interfere with each other. Otherwise, subjects may notice MTP latency more easily. Compared with 80°, the threshold is smaller in 40°, might be caused by the accumulation of two stimuli. But in MTR, the motion direction was only reversed once. In other word, there is only one stimulus of direction change. It seems that the rotation angle dose not affect perception threshold of the single stimulus.

Consistent with previous studies [3][7]-[9], angular velocity proved to affect the threshold (In MSA: $p = 0.0003 < 0.05$, In MTR: $p = 0.0057 < 0.05$). In both MSA and MTR, the value of threshold decreases as velocity increases in Fig. 5. That is, the perception threshold of added MTP latency is inversely to angular velocity. Since the inherent MTP latency was about 28.5 ms in our system, it was added to the thresholds in Table II to calculate the perception thresholds of total-MTP (TMTP) latency. In both motion events, inversely proportional models were respectively established to describe the relationship between TMTP latency perception threshold T_{TMTP} and angular velocity v as shown in (1) and (2).

$$\mathrm{MSA}: \quad T_{TMTP} = 51.57 + \frac{378.92}{v} \tag{1}$$

$$\mathrm{MTR}: \quad T_{TMTP} = 51.09 + \frac{196.56}{v} \tag{2}$$

C. User Acceptance of the Over-Threshold MTP Latency

When above the threshold, MTP latency could be noticed easily in virtual environment, but might be acceptable. User acceptance of the over-threshold MTP latency is described by three-level scores, including 1 (perceptible, but not annoying), 2 (annoying), 3 (very annoying). The higher the score, the more difficult it is to accept MTP latency.

The ANOVA method suggests that motion event has an impact on tolerance of MTP latency above the threshold (all $p < 0.05$). Fig. 4 (a) plots that subjects are more intolerable of MTP latency in Motion-To-Reverse than Motion-Static-Alternate, namely the direction reversal decreases user

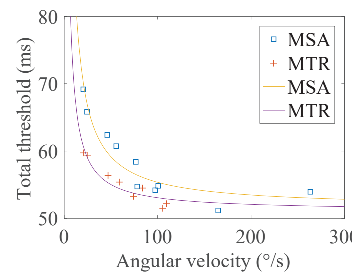


Fig. 5. Total threshold plots against angular velocity: points are values of total thresholds, curves are fitted models. The velocity is actual angular velocity.

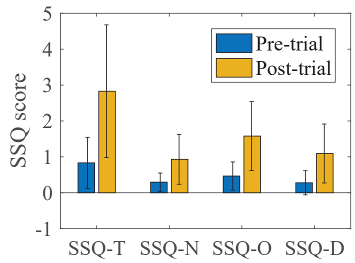


Fig. 6. The mean of SSQ scores with 95% CI

acceptance of the latency. And both angle (In MSA: $p = 0.0056 < 0.05$, In MTR: $p = 0.0214 < 0.05$) and angular velocity (In MSA: $p = 3.7862e - 12 < 0.05$, In MTR: $p = 4.1372e - 10 < 0.05$) also can influence perception of an over-threshold MTP latency . Fig. 4 (c) shows the greater angular velocity can make MTP latency more intolerable. Fig. 4 (b) shows that subjects are more likely to be disgusted with the latency when they rotate their heads 40° compared with 80°. Unlike perceiving whether there is a MTP latency which is a momentary perception, discomfort of the latency will last. Once an over-threshold stimulus occurs, subjects can notice the existence of the latency, and then generate some more advanced cognition, such as disgust, simulator sickness. When the stimulus disappears, subjects still need more time of non-stimulation to relieve discomfort. As the smaller angle makes a shorter time interval between stimuli, subjects would be more intolerable.

D. Simulator Sickness

Subjects were requested to answer SSQs at both beginning and end of each trial. There are four measured SSQ scores of pre-trial and post-trial, respectively, including total score (SSQ-T, 0∼48), nausea (SSQ-N, 0∼21), oculomotor (SSQ-O, 0∼21), and disorientation (SSQ-D, 0∼21) [18]. The higher the SSQ score, the more severe the symptoms is. Fig. 6 shows means of SSQ scores of subjects are all under a mild level (i.e., SSQ-T<16, SSQ-N<7, SSQ-O<7, and SSQ-D<7), and oculomotor is the most susceptible of three sub-symptoms in our experiment. After the VR experiment, SSQ symptoms are inevitably aggravated. Each trial is controlled within 20 minutes and an adequate rest is provided before the next trial. These can effectively prevent the deterioration of simulator sickness.

V. Conclusions

Head movements affect perception of MTP latency. Subjects have lower tolerance to MTP latency in MTR than MSA. In both motion events, when subjects experience smaller rotation angles or greater angular velocities, MTP latency becomes more unacceptable.

This paper observes that perception thresholds of MTP latency are 22.71∼40.70 ms. Since the inherent MTP latency is ∼28.5 ms in experiment system, the thresholds of total-MTP latency are 51.21∼69.20 ms. And inversely proportional models are created to characterize the relationship between thresholds and angular velocity.

In addition, visual cues are introduced to control subjects' head rotations. Little difference of head movements among subjects shows the effectiveness of the method.

VI. Acknowledgment

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