Psychophysical Detection Thresholds for Avatar's Leading Standing-Up Motion

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***Abstract*—In virtual reality (VR) systems, sensory feedback is inevitably delayed due to computational and system latencies. One potential solution to this problem is to predict the user's motion and generate avatar movements that slightly precede the user's current motion based on the prediction. To establish a fundamental criterion for such predictive avatar movements without causing user discomfort, this study investigated perceptually acceptable lead times using the psychophysical method of constant stimuli. While previous studies have focused primarily on acceptable delays in avatar motion, little attention has been given to the perceptual thresholds for motion precedence. In the experiment, participants stood up from a chair while their avatar in the VR environment stood up 0–60 ms earlier. Participants judged, using a two-alternative forced-choice procedure, whether the avatar's motion preceded their own. Detection thresholds were estimated by fitting the proportion of "preceded" responses to a normal cumulative distribution function. Across seven participants, the mean 50% detection threshold was 24.8 ms, and the 84% threshold was 39.7 ms. These findings provide a basis for implementing predictive avatar motion within perceptual tolerance, contributing to more seamless and comfortable VR experiences.**

***Index Terms*—method of constant stimuli, avatar, stand-up**

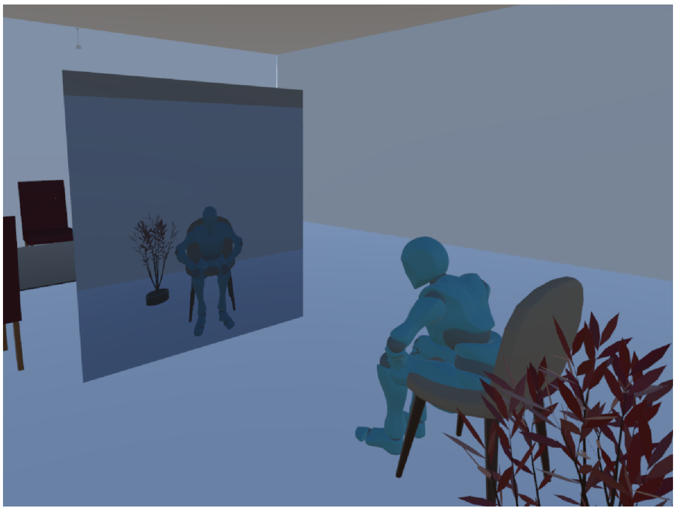

Fig. 1. VR environment with a mirror. A first-person perspective view of the avatar reflected in the mirror was presented to participants. The participant stood up from the chair to a fully upright position.

I. Introduction

In immersive virtual reality (VR) environments, sensory feedback, particularly visual feedback, inevitably lags behind the user's bodily movements. This delay also includes the latency in the avatar's motion within the VR environment. Because such delays can degrade the quality of the user experience, many previous studies have investigated acceptable levels of latency (e.g., [1], [2]). In contrast, cases where an avatar's motion precedes the user's movement have been scarcely examined. Such predictive leading by the avatar may compensate for the unavoidable delays inherent in VR systems [3]. Moreover, leading avatar motions could serve as a novel method to provide users with new sensory experiences, such as the sensation of their bodies feeling lighter [4].

The present study investigates, using psychophysical methods, the detection threshold at which users become aware that an avatar's motion precedes their own. Psychophysical methods offer a sophisticated approach for examining human perceptual responses and have been previously employed to assess detection thresholds for motion delays [1], [2], [5]. The detection thresholds obtained in this study could serve as a fundamental guideline for implementing naturally leading avatar motions within the range that users do not notice.

Another important aspect of this study is the involvement of vestibular sensations. Many of earlier researchers dealt with delayed hands motions [6]–[9]. In contrast, our target is standing-up motion from a chair, where vestibular, visual, and kinematic sensations are integrated for judging their temporal mismatch.

II. Methods

A. Apparatus and VR Environment

The participant was seated in a chair and wore a Meta Quest 2 headset (Meta Platforms, Inc., CA) to experience the VR environment, which was developed using Unity (2022.3.6f; Unity Technologies, CA). The system is considered to include an inherent delay of approximately 20 ms [10].

As shown in Fig. 1, a mirror was placed in front of the avatar within the VR environment, allowing participants to view their avatar through the reflection. When the participant stood up from the chair, the avatar simultaneously performed the same standing-up motion. The avatar's height was adjusted to match that of the participant, and the chair's height was modified to ensure that the participant's knee angle was approximately 90° while seated.

B. Stimuli: Leading Avatar's Motion

The avatar's standing-up motion was synchronized with that of the participant. However, once the motion was initiated, the avatar's movement could precede the participant's by a ms, where $a \in \{0, 12, 24, 36, 48, 60\}$ ms.

The preceding motion was implemented as follows: First, the velocity of the participant's head in the direction of gravitational acceleration was calculated using a Savitzky–Golay filter using a quadratic function. The filter window size was 21 with the sampling frequency being 72 Hz. Second, the position of the avatar's head was determined by multiplying the participant's head velocity by the lead time a. Finally, the avatar's animation corresponding to the calculated head position was displayed. This process was repeated in real time from the onset of the participant's standing-up motion until its completion.

C. Participants

Seven university students participated in this study after providing written informed consent.

D. Ethical Statement

This study was approved by Institutional Review Board, Hino Campus, Tokyo Metropolitan University (R7-075).

E. Procedures

First, as a practice session, participants performed the standing-up motion several times without lead time ($\alpha = 0$). During practice, participants were instructed to mimic the avatar's standing-up motion. Specifically, they placed each hand on the corresponding knee, stood with their feet shoulder-width apart, and tilted their upper body slightly forward before reaching an upright position.

Following the practice, participants experienced six lead-time conditions, each corresponding to a different value of a. Each set included the six conditions presented once in a randomized order, and the set was repeated ten times in total using a randomized block design. In each trial, participants performed the standing-up motion and subsequently answered whether the avatar's motion was perceived as leading or not, using a two-alternative forced-choice procedure.

F. Data Analysis

For each participant, the proportion of positive responses—where advanced motion was reported—at each stimulus level was approximated using a normal cumulative distribution function fitted via the maximum likelihood estimation method. The 50% and 84% thresholds were then determined based on the fitted function. The mean and standard error of these threshold values were subsequently calculated across participants.

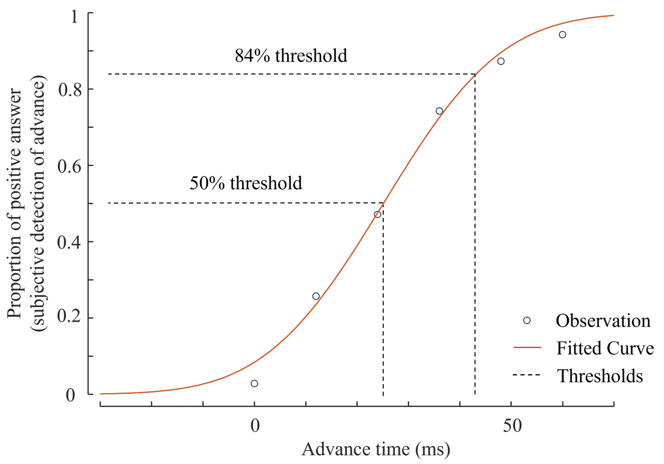

Fig. 2. Example of a psychometric curve calculated from all participants. The 50% and 84% thresholds indicate the lead time at which the avatar's motion was perceived as advanced in half or 84% of the trials.

TABLE I
RESULT OF DETERMINED 50% AND 84% DETECTION THRESHOLDS (MS).

Participant	50% threshold	84% threshold
A	30.0	38.1
B	26.2	39.4
C	22.3	42.9
D	35.5	48.8
E	33.6	51.4
F	16.4	37.7
G	9.7	19.8
All	25.0	42.9
Mean	24.8	39.7
Standard error	9.4	10.3

III. RESULTS

Fig. 2 shows the fitted normal cumulative distribution function to the proportions of all participants' answers as an example. Table I shows the 50% and 84% detection thresholds for each of seven participants (Participants A–G). The average value of 50% detection threshold among seven participants was 24.8 ms, and 84% threshold was 39.7 ms.

IV. DISCUSSION

This study demonstrated that motion advance is hardly recognized with a lead time of 24.8 ms or less. Olimov et al. [2] reported 50% and 84% detection thresholds for time delay as 129.70 ms and 204.30 ms, respectively, using a similar setup. These values are greater than those for the lead time. Users appear to perceive leading motion more readily than delayed motion. This asymmetry may stem from differences in the sense of agency. When the avatar moves ahead of the user, the sense of agency is more likely to be disrupted, increasing sensitivity. In contrast, delayed motion may still be perceived as causally linked to the user's action, leading to higher detection thresholds.

V. Conclusion

This study investigated the perceptual thresholds at which users detect an avatar's motion leading their own in a standing-up task within a VR environment. The results revealed that leading avatar motion is perceptually detectable at much shorter delays (mean 50% threshold: 24.8 ms; 84% threshold: 39.7 ms) than previously reported thresholds for delayed motion. The results provide a foundational guideline for designing predictive avatar control systems that maintain perceptual plausibility.

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