ELSEVIER
Journal of Neuroscience Methods 169 (2008) 255–266
JOURNAL OF NEUROSCIENCE METHODS
www.elsevier.com/locate/jneumeth

Action-perception patterns in virtual ball bouncing: Combating system latency and tracking functional validity

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Received 15 May 2007; received in revised form 15 November 2007; accepted 16 November 2007

Abstract

How can we evaluate the spatio-temporal performance of virtual environments (VE) for research use? Here we show that end-to-end latency (ETEL) of VE can strongly damage users' perceptual and perceptuo-motor behaviors and that it can be considered to be the key factor for evaluating face and functional fidelity of a VE. We used a virtual ball-bouncing task as a paradigmatic example. Ball bouncing is known to exhibit attractive and repelling states whose localization in the racket cycle is sufficiently thin to be changed by small variations of ETEL. We first present a simple test-bed to measure the intrinsic ETEL of research-related VE systems. We then report results of a psychophysical ball-bouncing experiment in which ETEL was manipulated. While face validity (i.e., subjective experience) was maintained with relatively high values, the results reveal that the perception-action behavior (performance) was damaged with smaller ETEL values. These results call for action-perception variables in order to test the fidelity of VE systems.

Keywords: Perception-action coupling; Sensory rearrangement; Ball-bouncing; Virtual reality; End-to-end latency

1. Introduction

Virtual environment (VE) technology is now extensively used for research in neuroscience, psychology or rehabilitation. Studies on perception (Beall et al., 1995), motor control (de Rugy et al., 2003; Tarr and Warren, 2002) or cognition (Klatzky et al., 1998; Peruch and Gaunet, 1998; Peruch et al., 1995) have embraced VE technology to better understand the mechanisms underlying human behavior. The intense use of VEs in these areas (see Loomis et al. (1999) for an exhaustive overview) can easily be explained by the immersive properties of large projection screens and head mounted displays HMD, and by the ease of controlling experimental parameters such as visual cues. In these research fields, the implicit assumption is that the knowledge gained from VE studies is the same as if experiments were performed in the real world: simulator validity is obviously a prerequisite. However, VE can present several limitations linked to the conception of the simulator engine (modeling the virtual world's physics), or to equipment performance (latency, update rate, resolution and accuracy). These limitations have prompted researchers to assess the extent to which such shortcomings can jeopardize the validity of their VE for studying human behavior. Among technological limitations, end-to-end latency (ETEL) (Ferrell, 1963; Smith and Smith, 1962; Sheridan and Zeltzer, 1994; Welch, 1978), update rate (Barfield et al., 1994; Watson et al., 1997), and field of view (Lapointe and Vinson, 2002; Peruch et al., 1997; Wells and Venturino, 1990) can have a major effect on perception and/or motor performance. However, some factors seem to be more critical than others when considering motor performance in the virtual world. For instance, the influence of ETEL on users' behavior seems to be larger than the influence of sensor inaccuracy, display resolution or display update rate (Ellis et al., 1999a). ETEL (equally called lag, or delay) corresponds to "*the time elapsed from motion of the user's instrumented hand* (...) *until representation of that movement in the display*" (Adelstein et al., 1996). The present study focuses on the damage caused by ETEL on the user's behavior.

Before assessing how ETEL can hamper motor performance, it is necessary to measure the value of ETEL, for which two

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doi:10.1016/j.jneumeth.2007.11.020

classical methods can be used. The first method requires two analog sensors in order to precisely time the occurrence of input (user's motion) and output signals (update in VE) (Bryson and Fisher, 1990). This method is accurate but requires extensive and careful technical manipulations. The second method involves video-based measurements of both input and output signals simultaneously. The signals are easy to record but provide less temporal accuracy (He et al., 2000; Mine, 1993; Miller and Bishop, 2002).

Despite the availability of several software (Garret, 2002) and hardware (Regan et al., 1999) optimization packages, it is impossible to completely cancel ETEL in a VE. The unavoidable latency may have detrimental effects both on the user's sense of immersion, as well as on her/his behavior. A subjective assessment of VE validity, called *subjective fidelity* (Riccio, 1995) or *face validity* refers to *the extent of subjectively experienced similarity between the simulator and the real-life situation* (Korteling and Sluimer, 1999), hence between the *simulator* and the *simulated* (Stoffregen et al., 2003). An approximate evaluation of such validity can be reached by questionnaires, for instance through the presence index (Slater, 1999; Slater and Usoh, 1993; Witmer and Singer, 1998). Concerning the VE's spatio-temporal performance, latency and update rate have been considered as factors affecting the user's sense of presence (Barfield et al., 1994; Sheridan, 1992). Psychophysical methods have been used to evaluate human sensitivity to temporal delay between the user's action in the real word and its display in the VE. An important feature of the VE upon which perception thresholds depend is whether the VE is head-slaved or not. If it is, the delay in the visual scene update leads to retinal slip when the user moves his/her head since the vestibulo-ocular reflex (VOR) shows small delays (≈16 ms) during passive head motion (Gauthier and Vercher, 1990) and anticipatory responses (≈−10 ms) during active head motion (Vercher and Gauthier, 1990). Above 2–3 deg/s, visual acuity drops, and retinal slip leads to oscillopsia, which refers to the perception that the visual world oscillates (Allison et al., 2001; Adelstein et al., 2003). This high human sensitivity to retinal slip puts strong constrains on VE set-ups, especially when using a HMD. Allison et al. (2001) reported that the oscillopsia threshold increased from about 60 ms to nearly 200 ms when head velocity was decreased from 90 to 22.5 deg/s. A latency greater than 150 ms in the visual feedback yields the feeling that the presented scene "swims" (Brooks, 1999). Finally, a value of 300 ms seems to destroy all immersive effects of the virtual environment (Stanney et al., 1998). When the VE display is slaved to the user's hand, thresholds of perceptual awareness of a visual delayed feedback range from 80 ms (Leube et al., 2003) to 150 ms (Franck et al., 2001).

However, exploiting a VE whose ETEL is subliminal does not guarantee that the collected behavioral data can be adequately interpreted. Indeed, latency, however small, may affect users' perception-action regularities irrespective of a "good" subjective experience. Validations of VEs that are designed for research applications should therefore primarily be concerned with *functional validity* (Korteling et al., 1997), also called *functional fidelity* (Moroney and Moroney, 1998) or *action fidelity* (Riccio, 1995), i.e., the extent to which *the behavior* (...) *of a person in the simulator resembles his or her behavior on the real task under the same condition* (Korteling et al., 1997). Indeed, the purpose of such a validation is to reduce the risk of erroneous conclusion concerning user's behavior. The negative impact of ETEL on motor performance, induced by perceptual and/or perceptuo-motor rearrangements (Welch, 1978), has been established in the pioneering work on tele-operation (Ferrell, 1963; Smith and Smith, 1962) as well as in more recent VE studies (Sheridan and Zeltzer, 1994; Welch, 1978). Up to now, the main point of the studies on the influence of ETEL on motor performance has been to show that users could adapt to relatively long delays (300 ms (Foulkes and Miall, 2000; Miall and Jackson, 2006)). When ETEL is above 80 ms in flight simulator control task (Wildzunas et al., 1996), 100 ms in human manual tracking task (Foulkes and Miall, 2000; Miall et al., 1985) or 130 ms in remote manipulation (Cunningham et al., 2001b), it always immediately causes disrupted performance, and functional validity of the VE is by definition impossible. Instead of characterizing how humans adapt to sensory rearrangements, our aim is to assess accurately the ETEL threshold below which the behavior in VE can be compared with the usual behavior, or conversely above which ETEL impairs the *functional validity* of a VE.

Despite their deceptive simplicity, ball-bouncing situations are highly relevant to illustrate the issue of VE validation for research use. Computational, perceptive and perceptuo-motor reasons justify their use for testing both the *face validity* and the *functional validity* of a VE set-up. The computation and rendering of realistic collisions are a difficult feat from a technical viewpoint (Mirtich, 1996, 2000). On the perception side, the collision paradigm offers a kind of task frequently performed in everyday life or in sport leisure; human sensitivity to the physical properties of collisions is consequently naturally high (e.g., Nusseck et al., 2007). From the dynamics of real collisions, humans can assess several properties of objects such as relative mass (Flynn, 1994) or elasticity (Couroussé et al., 2006). Auditory and visual specifications are also efficiently used to control bounce passes (Warren et al., 1987). Such studies performed in the real world provide to the VE designer a good basis of comparison for demonstrating the validity of the engine. Indeed, experimental works on VE have also demonstrated the good sensitivity of humans to anomalies during the rendering of colliding objects (O'Sullivan and Dingliana, 2001; O'Sullivan et al., 2003). Therefore, the ball-bouncing task appears appropriate for testing face validity.

Other paradigmatic examples of ball bouncing for testing VE set-ups are provided by human-in-the-loop studies. The ball-bouncing task is a rhythmic task in which regular bounces are achieved by hitting a ball with a vertically oscillating planar surface. In ball bouncing experiments, racket acceleration at impact (ACC) is used as *the* key variable to investigate the human ability to exploit a physical property of the ball-racket system: dynamical passive stability (Schaal et al., 1996; Sternad et al., 2001). When the racket hits the ball with negative acceleration – in what is called "*a dynamical attractor*" – small perturbations in ball motion (e.g., vertical velocity) do not need to be corrected, and ball trajectories relax back to a limit-cycle behavior within a few cycles without any active control of the racket. Two distinct virtual ball-bouncing set-ups have been recently developed in order to assess whether participants exploit the passive dynamical regime when performing the ball-bouncing task (de Rugy et al., 2003; Morice et al., 2007). However, in such ball-bouncing VEs, ETEL can induce wrong software computation of racket velocity and consequently wrong ball motion. Moreover, ETEL may possibly jeopardize the user's exploitation of the stability regime or even prevent users from finding this regime.

Recently, with one of the above-mentioned VEs, Morice et al. (2007) have created new ball-bouncing conditions by introducing a temporal delay between the motion of the physical racket and the virtual racket. In all delay conditions (ranging from 83.75 to 335 ms), the behavior of participants was initially disrupted. After fifty 40-s-long trials, participants learned to maintain bouncing just outside the passively stable region, indicating (perceptually based) active stabilization. This suggests that the exploitation of dynamical passive regime in ball bouncing is endangered by delayed visual feedback. Participants recovered the adequate bouncing pattern (impacting the virtual ball half-way through the upswing motion of the virtual racket cycle) by adjusting the impact phase within the physical racket. These adaptations show that, across exposure to visual delayed feedback, participants learn to compensate for the presence of ETEL. Indeed, new behavioral solutions may be discovered and stabilized through learning. In sum, the ball-bouncing task is simple, sensitive to the presence of ETEL, and human behavioral responses to the dynamical attractor can be pertinently used for testing the functional validity of VEs.

Since there are no generic tools for evaluating the subjective or functional fidelities of research-devoted VEs, the present article pursues two goals. First, we present a simple method accessible to a large audience for the measurement and the reduction of ETEL in VE equipment such as our virtual ball-bouncing set-up. Second, we report a psychophysical and behavioral experiment based on a simple motor task involving a tight coupling between perception and action, with which we tested various perceptuo-motor thresholds in response to ETEL increments.

2. Measuring and reducing ETEL in VEs

2.1. Equipment and task

2.1.1. General purpose of the VE set-up

A global illustration of our VE layout is given in Fig. 1. Participants were asked, in successive trials, to hit the virtual ball with the racket and to maintain this rhythmic bouncing movement for the duration of the trial. A virtual target was visible on the screen, and bouncing had to be such that after each impact the ball bounced as close as possible to the target. To facilitate consistent bouncing periods, a computer-generated metronome signal (beep frequency of 1.54 Hz, equal to 650 ms/cycle) was used to prescribe the racket cycle period. Participants were instructed to synchronize the timing of impacts with metronome beeps throughout the entire trial. The following paragraphs detail the specification of each part of the real-time pipeline.

2.1.2. Electromagnetic tracker and racket

In our experiments, participants held a physical table tennis racket in their preferred hand, which could be moved freely in three dimensions. On the back side of the physical racket, at 0.2 m from the tip of the racket handle, the sensor of a single unit electromagnetic tracker (flock of birds (FOB), Model 6DFOB©, Ascension Technologies) running at a sampling rate of 120 Hz was attached with a plastic screw. The transmitter base of the FOB (serving as a space reference) was positioned on a post so that the sensor was directly facing it (see Fig. 1). Position and orientation signals were sent via a serial RS-232 communication port to a custom-written software running on the host computer.

2.1.3. Host computer and simulation engine

From the vertical position signal of the physical racket, the virtual application – treated in real-time priority on the host computer (MS Windows XP Pro©, bi 2.6 GHz Pentium processor, 512 Mo RAM, graphic engine Saphire Radeon 9600 ATI Technologies Inc.) – computed online the position and interaction of the "virtual racket" and the "virtual ball" visible on the screen.

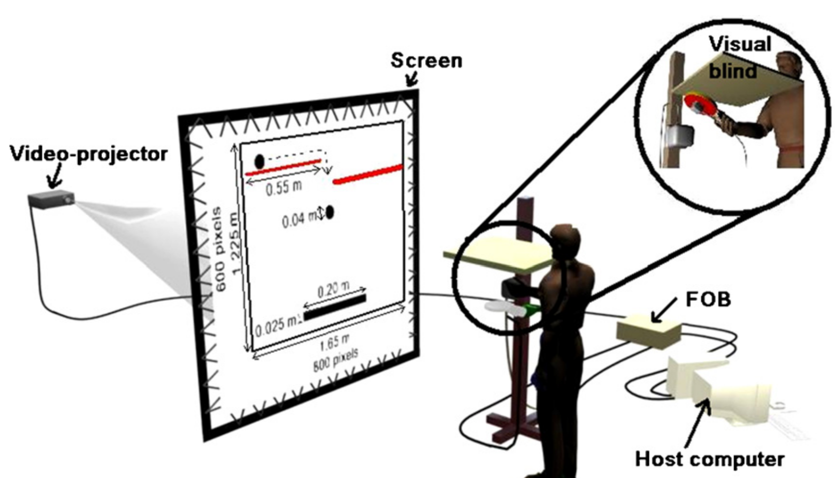

Fig. 1. General view of the virtual reality ball-bouncing set-up, the position of the electromagnetic sensor and of the transmitter facing the physical racket.

2.1.4. Audio stimuli

The SDL library was used for playing metronome and impact sound, with an audio mixer tuned for four tracks. Mono soundtracks (16 bits 11025 Hz) were mixed by step of 512 samples. We assumed that the sound latency was 40 ms maximum (512/11025 = 40 ms) and 20 ms in average. Four to six samples of metronome and impact sounds could be played simultaneously. Latency between contact detection and sound play was equal to 2 ms.

2.1.5. Visual stimuli

The VE background was colored in pure white and did not contain any texture. OpenGL and SDL libraries were used for the display. The ball was displayed as a set of 100 polygons, depicting a black circle of 0.02 m radius. There was no geometric shape smoothing. The vertical displacement of the "virtual racket" was displayed on an LCD projector (50 Hz) as a horizontal black rectangular bar on a large screen (2.70 m width × 1.25 m height, resolution equal to 800 × 600 pixels) positioned in front of the subject, so that the eyes were about 1.5 m from the screen. Before the experiment began, participants were asked to keep the racket in their preferred hand at a comfortable height (elbow flexed approximately at 90°). The racket position was then measured and taken as a zero/reference position. Participants then stood upright in front of a sheet of cardboard (visual blind) positioned well above the hand, which prevented them from seeing their hand during the trial. A virtual horizontal line, colored in red (0.006 m height × 0.55 m width) and serving as a target for the ball could be presented at a chosen height above the reference position of the racket. This target was projected on the right side of the screen. The coefficient of restitution (α) of the ball-racket system was equal to 0.5. The vertical displacements of virtual ball and racket were simulated in a constant gravity field ($g = 9.81\ m/s^2$). The simulation engine emulated a virtual ball weighing 0.027 kg.

The start of the simulation, namely the falling of the ball, simultaneously triggered the stream of the FOB data and initialized the clock. The data time stamps were provided with a 1 ms resolution by the clock of the FOB computer processor unit.

2.1.6. Implementation of a predictive filter

The FOB device comprises three FOB hardware filters: two analogical filters "AC WIDE", "AC NARROW" and one digital "DC FILTER". These filters are dedicated to noise reduction in measurement signals. While the two analog filters provide the average of several data positions, the digital filter is based on weighted averages of successive position/angles measurements according to assumed noise values. The combination of these filters is therefore time-consuming and leads to a variable latency.

By disabling the three noise filters, we expected to reduce ETEL (see Section 2.2), but the noise level was increased at the same time. We created a software algorithm that operated on memorized measurements to significantly reduce ETEL, while at the same time keeping the noise level close to minimum. The reduction of noise was accomplished by a moving average of memorized data positions. The reduction in ETEL was obtained by the extrapolation of the future virtual racket position based on the kinematics of the most recently memorized positions of the physical racket, using a third order polynomial regression function. However, in this procedure, the main difficulty was to optimize the prediction function. Indeed, too much prediction could be detrimental to accuracy in physical racket components. As presented in Table 1, preliminary testing showed that reduction of end-to-end latency achieved by 16.66 or 24.99 ms predictions (2 or 3 samples) led to lower predicted racket velocities than the monitored physical racket velocity, and to an important variability in velocity error. Consequently, these two anticipation ranges were not used. The best performance was found with a reduction of ETEL by the equivalent of one sample (8.33 ms). Such an anticipation range also succeeded in reducing the noise in the virtual racket signal (the positional RMS error of the virtual racket was less than 3.8 mm when the physical racket was 0.20 m away from the FOB transmitter[1]). Mathematical implementations of our predictive filter are described in Appendix.

2.2. Experimental test-bed to measure ETEL

Here we present the two-step method used to measure ETEL in our virtual ball-bouncing set-up. An accurate measurement (0.5 ms accuracy) of ETEL baseline value was first performed with an analog test-bed with the predictive filter disactivated. A second step with an alternative methodology was needed to measure ETEL after the implementation of our predictive filter. This second test-bed gave an accuracy of 2 ms and served as a routine check. These two methods are therefore complementary.

2.2.1. Analogical measurement of ETEL baseline value

As mentioned above, the FOB device implements three FOB hardware filters (two analog called "AC WIDE" and "AC NARROW", respectively and one digital called "DC FILTER"). The FOB also allows two data retrieving modes ("positions" or "positions and angles"). Therefore, eight conditions combining four filter types (None, Wide, Narrow, DC) and two data retrieving modes can lead to various ETEL values. The objective of the first test-bed was to measure the respective influence of these FOB settings in the magnitude of ETEL. Twenty-five discrete FOB sensor movements were consecutively recorded in each condition. The test-bed ran as follows: the physical racket was placed on a bar serving as a pivot (cf. Fig. 2). Pressing abruptly on the end of the bar induced a sudden and almost vertical motion of the FOB sensor. A 1D accelerometer (Entran® EGAS—FS-5) fixed onto the physical racket next to the FOB sensor was used to detect the initiation of the physical racket motion. A photodiode (Burr–Brown® OPT301) was used to detect the beginning of the virtual racket motion. It was positioned close to the screen where the virtual racket was displayed at its initial position. The detec-

[1] The maximal amplitude of the physical racket displacement (defined as maximal vertical position minus minimal vertical position) usually monitored is inferior to 0.4 m and corresponds to a maximal distance of 0.20 m between the FOB sensor and transmitter.

Table 1
Computation of position and velocity errors between monitored position of the physical racket and predicted position with a polynomial regression (third order)

		Errors	1 sample prediction (8.33ms)	2 samples prediction (16.66ms)	3 samples prediction (24.99 ms)
Position	(m)	Mean	0.0005	-0.0034	0.0045
		Std	0.0013	0.0066	0.0066
		RMS error	0.0012	0.0057	0.0057
		Max	0.0020	0.0027	0.0132
Velocity	(m/s)	Mean	0.2925	-0.0983	-0.4521
		Std	0.1278	0.3878	1.0879
		RMS error	0.1107	0.3355	0.9421
		Max	0.3736	0.1353	1.1622

The grey column represents the predictive window chosen (8.33 ms).

tor surface (2.29 mm × 2.29 mm) was smaller than the racket thickness. Therefore, before any motion occurred, the diode signaled "darkness". The diode was placed with great care on the brim of the virtual racket so that the diode would indicate "light" as soon as the virtual racket motion occurred. Both accelerometer and diode outputs were recorded at 2000 Hz (DataLINK Model DLK800, Biometrics Ltd., UK) using a second PC (PC2, Pentium III, 498 MHz, 256 MB RAM, ms Windows© XP SP1, graphic engine ATI Technologies Inc., 3D RAGE PRO AGP 2×).

Matlab® routines were developed to compute the delay between the two signals (accelerometer/diode) for each single racket motion, and the 25 values were then averaged within each condition (cf. Table 2). In the eight conditions, ETEL ranged from 37.0 ± 11.1 ms (mean ± S.D.) to 72.0 ± 9.0 ms (Table 2).

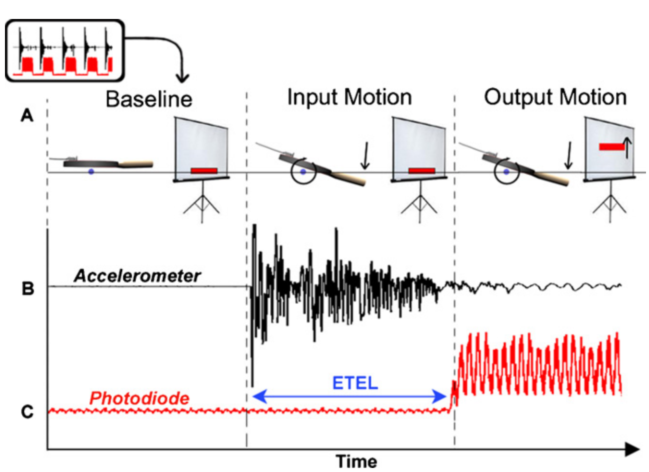

Fig. 2. Analog test-bed used to measure the end-to-end latency (ETEL) in our experimental virtual ball-bouncing set-up. For each of the 25 consecutive records (see inset), physical and virtual events have three parts. (A) Pictorial sketch of the events during the analog ETEL measurement. The occurrences of physical and virtual racket movements are depicted regarding their respective analog output. (B) The 1D accelerometer fixed onto the physical racket displayed no change during the baseline condition. It was used during the input condition to detect the beginning of the physical racket motion. (C) The photodiode displayed no change during the baseline and input motion condition. It was used during the output motion condition to detect the beginning of the virtual racket motion. ETEL was computed as the time elapsed between the accelerometer and the diode output.

The smallest ETEL values were obtained when all filters were removed. The variability in the latency measurement was caused by the difference in the update rates of the flock of bird (120 Hz) and the video-projector (50 Hz), as well as by the lack of synchronization between the two components. We chose to maintain the FOB maximal update rate at 120 Hz to overcome the FOB measurement latency.

2.2.2. *Video-based measurement of assessing ETEL reduction*

The predictive filter was designed to run on continuous displacements (third-order polynomial regression is optimized for regular bouncing). For this reason, the sudden and vertical motion of the physical racket previously used to estimate ETEL was inappropriate to test the predictive filter. In a second step, we used a numerical video camera (Canon® XM1, sampling rate = 50 Hz, de-framed) to record simultaneously the oscillatory motion of both the physical and the virtual racket. Data[2] from one subject were obtained during nine 23-s-long trials with a target height of 0.55 m. For each of the nine trials tested, ETEL values were computed as the mean time elapsed between consecutive maxima of physical and virtual racket positions. After implementation of the predictive filter, mean ETEL over the nine trials was equal to 29.78 ± 1.07 ms (mean ± S.D.) this value being consistent (with the gain of one sample −8.33 ms) with the previous ETEL test-bed (37–8.33 ≈ 28.67 ms).

3. Evaluating the perceptuo-motor consequences of ETEL

3.1. *Participants*

Fourteen adults (9 M and 5 F, aged 25.1 ± 4.2), naive to the exact purpose of the study, participated in this experiment. They had a limited practice experience of 2 h in a previous visually delayed ball bouncing study and were thus familiar with the VE. All had normal or corrected-to-normal vision and no known neuro-motor impairment.

[2] Signal acquisition and digitizing were performed with the Snap 32 software (Biometrics©, France).

Table 2
ETEL measurements of our VE set-up according to the FOB hardware filter manipulations, and after implementation of a customized predictive filter

Filter activated	FOB filter AC wide + DC		FOB filter AC wide		FOB filter DC		All FOB filters removed		Customized predictive filter
Data retrieving	X, Y, Z[a]; A, E, R[b]	X, Y, Z	X, Y, Z	X, Y, Z; A, E, R	X, Y, Z; A, E, R	X, Y, Z	X, Y, Z	X, Y, Z; A, E, R	X, Y, Z; A, E, R
Mean (ms)	72	69.54	62.81	55.74	52.90	49	39.1	37.3	29.78
S.D.	9	10.01	6.7	9.6	8.2	6.7	8.4	11.1	8.27

[a, b] Modes: position: X, Y, Z; orientation: A, E, R

3.2. Experimental procedure

In this experiment, the end-to-end latency of the set-up (ETEL) was manipulated by adding different fixed delays to the minimum ETEL value of the system (29.78 ms). The increment size of the added delays was 20 ms due to the video-projector's 50 Hz update rate (Adelstein et al., 2003; Ellis et al., 1999b). The added delays ranged from 0 to 160 ms, thus by steps of 20 ms, giving nine different ETEL values (or experimental conditions): 30–50–70–90–110–130–150–170–190 ms. Each subject performed ten 20-s-long trials in each condition. Conditions were presented in random order.

3.3. Experimental design

Participants were tested in two experimental sessions, spread over 2 days. Session order was counterbalanced among subjects. During one session (WB: with ball), participants were instructed to regularly bounce the virtual ball with the racket in order to reach a virtual target (a horizontal bar) located at 0.55 m above the zero position of the racket (the vertical position of the racket when the participant's elbow was flexed approximately at 90°). They could hear a sound when the ball hit the racket and had to synchronize the timing of collisions with the metronome beat (650 ms period) while maintaining the rhythmic bouncing action throughout the entire trial. During the other session (NB: no ball), no ball was present in the virtual world: no visible ball and no impact sound. Subjects were instructed to displace the physical racket smoothly and vertically back and forth to produce a paced virtual racket displacement synchronized with the metronome beat, over the entire trial. No instructions were given about racket amplitude.

After each trial, subjects verbally reported to the experimenter whether the visual feedback (virtual racket) of their action (physical racket) was perceived as delayed or synchronous. In other words, they had to judge the synchrony of the two racket displacements. No instruction was given about features to use when making the judgment, and so participants were free to form their own criteria.

3.4. Psychophysics analyses

Verbal reports from each subject were analyzed separately for each experimental session (NB and WB, respectively) to provide for each ETEL value an individual mean likelihood, expressed in percentage. Hundred percent corresponded to the detection of ETEL in all 10 trials, and 0% in none of them. The individual cumulated data were then fitted (least square procedure) by the best logistic functions ($r^2 > 0.85$ and $r^2 > 0.54$ for NB and WB, respectively). The resulting logistic fits were then used to derive the point of subjective equality (PSE) and the just noticeable difference (JND) (Gescheider, 1997) for each subject in both sessions.

Individual PSEs and JNDs are reported in Table 3. The values indicate that for 9 of the 14 subjects, PSE was superior when no interaction with the ball occurred (NB) than when it occurred (WB). The minimum PSE value was 45.71 ms under

Table 3
Individual and average PSE and JND values for the best logistic fit in the two experimental sessions

	No ball interaction (NB)		With ball interaction (WB)	
	JND (ms)	PSE (ms)	JND (ms)	PSE (ms)
S01	33.55	91.33	11.53	86.69
S02	10.75	89.52	8.87	99.78
S03	33.95	45.71	27.73	51.09
S04	15.22	111.65	26.33	88.26
S05	47.71	101.65	22.99	57.5
S06	14.26	97.04	10.83	116.81
S07	29.46	106.92	32.48	71.85
S08	12.93	99.78	100.66	12.26
S09	13.87	81.03	14.37	83.62
S10	26.27	171.01	30.18	112.85
S11	42.39	59.32	30.54	27.43
S12	30.46	98.25	10.68	80.28
S13	33.58	126.84	35.13	104.2
S14	15.4	105.29	13.16	130.92
Mean	25.70	98.95	26.82	80.25
S.D.	11.98	29.25	23.22	33.84

NB sessions and 12.26 ms under WB sessions. Moreover, JND values revealed that for 8 of the 14 participants, individual values were superior for NB sessions. The minimum JND values were 10.75 ms in NB sessions and 8.87 ms in WB sessions.

The mean of PSE values across all subjects was 98.95 ± 29.25 ms (mean ± S.D.) for NB and 80.25 ± 33.84 ms for WB, paired $t(13) = -2.22$, $p < .05$. Participants thus discriminated the presence of ETEL "earlier" in WB sessions than in NB sessions. No significant difference was found in JND between NB (25.70 ± 11.98 ms) and WB (26.82 ± 23.22 ms), paired $t(13) = -0.15$, $p > 0.05$, indicating that participants discriminated the latency with the same accuracy whether or not (visual/auditory) the ball–racket interaction was available.

Individual mean likelihoods from each session were pooled together for each ETEL and then fitted by the best mean logistic function. Average logistic curves with average JND and PSE for the two experimental conditions are plotted in Fig. 3A and B.

3.5. Behavioral analyses

Similar behavioral analyses were conducted across NB and WB sessions on the virtual racket period (PER_V), defined as the mean difference between successive maximum racket positions within a trial. During NB sessions, PER_V values were maintained around 0.599 ± 0.010 s over ETEL conditions, while during WB sessions, PER_V values decreased from 0.616 ± 0.020 to 0.574 ± 0.053 s over ETEL conditions. All PER_V values were significantly inferior to the period prescribed by the metronome (comparison tests to 0.650 s, $p < 0.05$). A repeated measure ANOVA (2 sessions × 9 ETEL) performed on PER_V values revealed significant main effects for session ($F_{(1,26)} = 8.48$, $p < 0.05$), ETEL condition ($F_{(8,208)} = 2.34$, $p < 0.05$). The interaction between these two factors also reached significance ($F_{(8,208)} = 5.24$, $p < 0.05$). A Newman-Keuls post-hoc test revealed that significant changes in PER_V values between NB and WB sessions occurred for ETEL values larger than 130 ms, above the two PSE thresholds. Consequently, the difference in PSE values between NB and WB sessions cannot be explained by behavioral differences across ETEL conditions, such as movement periodicity, but perhaps by the availability of additional information provided by elastic collisions during the WB session.

In addition to PER_V, behavior analyses in the WB session focused on performance and racket kinematics. First, bounce error (ERR_B), the performance index, was calculated as the within-trial mean of the distance (in m) between peaks of the ball trajectory (following the last impact in each racket cycle) and the target. Second, physical and virtual racket accelerations at impact (ACC_P and ACC_V, respectively) were also computed. The racket acceleration at impact was previously shown to be a key variable for understanding racket control in ball bouncing (Dijkstra et al., 2004; Schaal et al., 1996). It was used to demonstrate that participants were guided by the passive stability properties of ball bouncing (Sternad et al., 2001). In this experiment, since the displacements of both rackets were desynchronized, acceleration of both rackets at impact had to be computed. Mean values per subject for these three dependent variables were analyzed separately for each ETEL condition and then averaged across subjects.

3.5.1. ERR_B

Mean ERR_B values were equal to -0.01 ± 0.09, -0.02 ± 0.12, -0.02 ± 0.11, -0.02 ± 0.12, -0.03 ± 0.13, -0.03 ± 0.12, -0.05 ± 0.14, -0.07 ± 0.14 and -0.07 ± 0.16 m for ETEL values ranging from 30 to 190 ms (fixed steps of 20 ms), respectively (Fig. 4A). Because the ball had a radius of 0.02 m, mean values of ERR_B performed in the 30–110 ms ETEL conditions were thus quite perfect. However, the standard deviation of ERR_B showed an increase with ETEL, preventing any parametric statistical analysis. We computed $\log(ERR_B + 1)$ to

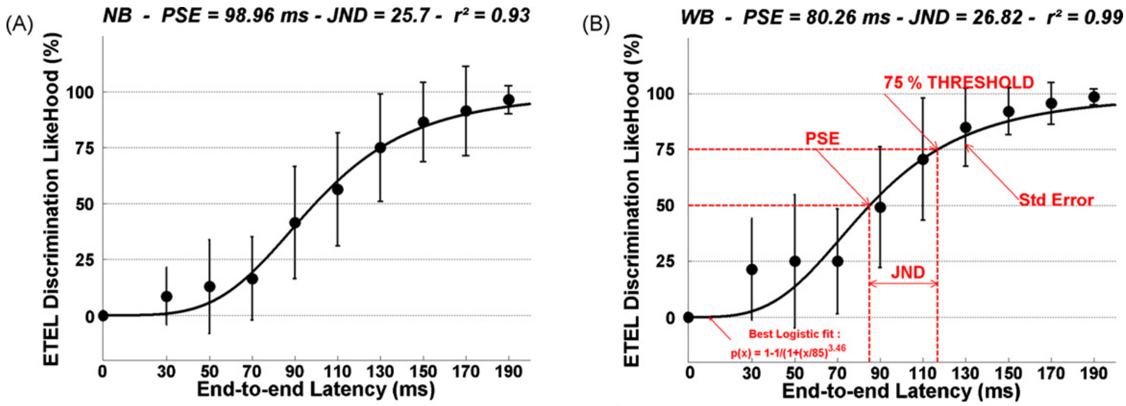

Fig. 3. Across participants mean psychometric function for (A) No ball condition (NB) and (B) With ball condition (WB), with point of subjective equality (PSE, i.e., 50% discrimination threshold), just noticeable difference (JND, i.e., 75–50% discrimination threshold) and r^2.

obtain a homogeneous variance of this dependant variable (Levene's test for homogeneity of variances, $p > .05$). A repeated measures ANOVA (9 ETEL conditions) showed a significant effect of ETEL on $\log(ERR_B + 1)$ ($F_{(8,1251)} = 16.75$; $p < 0.05$). Newman-Keuls post-hoc tests showed that $\log(ERR_B + 1)$ values corresponding to the ETEL values equal to 110–190 ms were significantly different from the smaller ETEL conditions, indicating a degradation in the performance above 110 ms. Standard deviation of ERR_B values within each bouncing trial (S.D. ERR_B) were also averaged across ETEL conditions (Fig. 4A). S.D. ERR_B linearly increased with ETEL ($N = 9$; $r^2 = 0.82$).

3.5.2. ACC_P and ACC_V

While ACC_P mean values ranged from -7.09 ± 2.42 to -11.28 ± 3.26 m/s^2, ACC_V mean values ranged from -3.40 ± 2.60 to 2.43 ± 4.01 m/s^2, with a switch from negative to positive values between 50 and 70 ms of ETEL (Fig. 4B). A repeated measures ANOVA showed a significant effect of ETEL on ACC_P ($F_{(8,1251)} = 31.19$; $p < 0.05$) and a Newman-Keuls post-hoc test showed that all ETEL conditions differed from each other. This result suggests that small changes in ETEL (20 ms step), lead to significant behavioral changes. Moreover, a repeated measures ANOVA showed a significant effect of ETEL on ACC_V ($F_{(8,1251)} = 38.54$; $p < .05$) and a Newman-Keuls post-hoc test showed that ACC_V values corresponding to 30, 50 and 70 ms of ETEL conditions (i.e., in the negative range) significantly differed from the other conditions (in the positive range).

4. Discussion

A reliable measure of the end-to-end latency (ETEL) of any VE system is essential when studying cognitive and perceptuo-motor components. Two complementary methods to measure ETEL in a VE were presented here as a baseline requirement. Furthermore, we validated the use of a simple prediction routine leading to a beneficial reduction of ETEL. The main contribution of the present work is the psychophysical demonstration of an ETEL effect on action-perception bouncing behaviors. The results provide a perceptual and behavioral basis for comparison to gauge the human sensitivity to ETEL, which is then related to the measured spatio-temporal performance of our VE. We demonstrated that: (i) the awareness of ETEL was improved by the availability of additional information provided by elastic col-

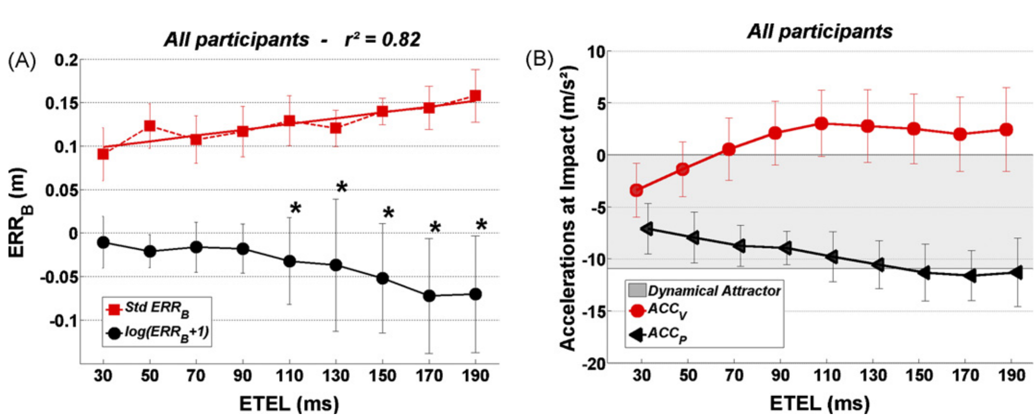

Fig. 4. (A) Mean transformed target error ($\log(ERR_B + 1)$) and standard deviation of target error (S.D. ERR_B) plotted as a function of end-to-end latency (ETEL). Star symbols represent the $\log(ERR_B + 1)$ values differing significantly from the other values across ETEL conditions. (B) Acceleration of the physical racket at impact (ACC_P) and acceleration of the virtual racket at impact (ACC_V) plotted as a function of ETEL. While ACC_P remained in the negative range throughout all ETEL values, ACC_V switched from negative to positive, and hence from a passive to an active racket control when ETEL exceeded 50–70 ms. Vertical bars represent the standard deviation of mean values.

lisions between a virtual ball and racket and that (ii) ETEL had a larger effect on the regulation of bouncing than on the conscious perception of bouncing events.

4.1. Measuring VE latency

An analog method and a video-based method were used to measure ETEL in our virtual ball-bouncing set-up. The two methods appear complementary. The analog method gives an accurate measure of ETEL for sudden inputs, in the range of high accelerations/frequency, and at the far-end of human movement possibilities. The video-based method, although limited in temporal precision by the frequency-rate of the video camera, allows the measurement of ETEL with good precision (when the predictive filter is implemented) in natural, continuous tasks, and with standard equipment. The minimum ETEL value of our VE apparatus (≈30 ms) is comparable to that of other VEs used for research: 33 ± 5 ms (Adelstein et al., 2003), 27 ± 5 ms (Ellis et al., 1999c), and <30 ms (Franck et al., 2001).

4.2. Conscious awareness of VE latency

Our psychophysical experiment showed that the two threshold values of ETEL perception – 80 and 99 ms PSE values found in NB and WB, respectively – are consistent with the 80 ms value found by Leube et al. (2003), but inferior to the 150 ms value found by Franck et al. (2001) in similar studies. These PSE values are well above (at least by 50 ms) our VE's minimum ETEL. Our VE's spatio-temporal performance can therefore be judged as being good enough for users to perceive the virtual racket motion as realistic. The *face validity* of our VE was thus successfully demonstrated.

The significant difference found in PSE between NB and WB conditions confirmed our hypothesis that the collision between racket and ball provided participants with additional information they could pick up in the WB condition. Through ball kinematics, such as velocity changes around the impact, or bounce amplitude, information related to the elasticity of the collision (Warren et al., 1987), mass of the ball (Runeson and Vedeler, 1993; Todd and Warren, 1982), or in our case delay between the expected physical collision and the occurrence of the virtual collision can be perceived by participants. We can also speculate that participants, when asked to interact with the virtual world, were more immersed in the environment or more attentive to its fidelity. Such focus on the realism of the virtual world provides a tentative explanation for the smallest individual PSE observed (≈13 ms). Indeed, participant S08, who exhibited a PSE value smaller than the minimum investigated ETEL (≈30 ms), may have relied on a realism criterion rather than on a targeted criterion related to the synchrony between physical and virtual rackets when answering the forced-choice question. Consequently, S08 might have behaved as if he/she had detected an anomaly in the virtual world, while not necessarily being explicitly aware of the presence of ETEL. Concerning perceptual discrimination of ETEL, although no difference was found in JND values between the two sessions, the average JND value of 25 ms confirms Ellis et al. (1999a,b,c)'s suggestion that human observers are able to detect changes in latency less than 33 ms and perhaps 16.7 ms (Jung et al., 2000).

4.3. Behavioral responses to latency and functional validity of VE

In order to test the functional validity of our ball bouncing VE, we analyzed the changes of several behavioral responses according to the ETEL manipulation. A threshold of performance damage (measured in terms of bouncing error ERR_B) was obtained when ETEL reached 110 ms. The deterioration in ERR_B when ETEL was above this value matches the thresholds for mean error degradation found in other studies: 80 ms during operational flying (Wildzunas et al., 1996), 130 ms in remote manipulation (Cunningham et al., 2001b). One cannot exclude the fact that the high performance of participants when ETEL values are kept within a limited range (up to 110 ms in ball bouncing) was obtained through a change in the behavior, with respect to "natural" behavior in the real world. Indeed, many experimental studies have shown that, when exposed to visually delayed feedback, sensori-motor adaptation (Cunningham et al., 2001a; Foulkes and Miall, 2000; Miall and Jackson, 2006) or motor learning (Morice et al., 2007) take place. Consequently, the functional fidelity of a VE cannot be tested solely through the analysis of average performance because an *average* high performance can be reached with subtly impaired behavioral responses.

Evidence for this conjecture was first provided by analyses of performance variability. Indeed, while no deterioration was observed in mean performance error for ETEL up to 110 ms, variability of performance error (S.D. ERR_B) was instantaneously affected by ETEL in a linear way. This change in ERR_B variability following the increase in ETEL resembles the gradual decrement in performance with delay observed by Day et al. (1999) in a control task of remote vehicle performed with delayed feedback. It also reproduces the linear relationship between error and delay found by Adams (1961) in a tracking task and by Bryson and Fisher, 1990; Bryson, 1993 in a fitts task. Based on these observations, it is readily apparent that the degradation in ball bouncing performance (measured by mean and standard deviation values of ERR_B) is dependent on ETEL. Moreover performance variability analyses seem to be more suited for the evaluation of functional fidelity than mean error analyses. Indeed, the demonstrated linear degradation of performance variability allows us to state that the perception-action behavior is damaged quite instantaneously when ETEL is increased.

A second piece of evidence for the use of targeted analyses instead of classical mean error analyses, when testing functional validity, was found through human attunement to dynamical regimes of the ball-bouncing task. As presented in the introduction, racket acceleration at impact (ACC) is used as a key variable to investigate the human ability to exploit task attractors and passive stability regimes (Schaal et al., 1996; Sternad et al., 2001). Recently, negative values of virtual racket acceleration ACC_V ($-2.16\ m/s^2$) were observed for participants bouncing in a VE, as predicted by the passive stability model (de Rugy et al., 2003). When our VE was set in its minimal ETEL configuration, ACC_V was also in the negative range ($-3.40 \pm 2.60\,\text{m/s}^2$, see Fig. 4B). When ETEL however exceeded 50–60 ms, the bouncing behavior became unstable, fell in the positive regime, and required active control. This is because impact acceleration of the *virtual* racket was shifted to positive values while subjects manipulated the *physical* racket in the negative range. In that situation, our participants simply could not exploit the stability regime without modifying their natural behavior (i.e., hitting the ball later in the physical racket cycle). The second piece of evidence for claiming that the ETEL increase leads to an earlier damage on perception-action coupling than on its conscious awareness is provided by the relatively linear increase in ACC_V values in the (30–90 ms) ETEL range. As shown by Dijkstra et al. (2004), particular values of ACC_V provide a maximum range of bouncing stability. Specifically, a system with a coefficient of restitution α and the gravitational constant g is passively stable if racket acceleration at impact remains between 0 and $-2g(1+\alpha^2)/(1+\alpha)^2$. For example, with $\alpha = 0.5$ and $g = 9.8\,\text{m/s}^2$, racket acceleration must be in the negative range between 0 and $-10.9\,\text{m/s}^2$. In this global range, Lyapunov local stability analyses even reveal a much smaller region of maximal stability between -2 and $-5\,\text{m/s}^2$ (Sternad et al., 2001). Consequently, the presence of ETEL prevents the exploitation of the region of maximum stability, even allowing participants to bounce the ball with negative racket acceleration at impact.

The observed threshold between the passive to active regimes can also explain the ETEL-related increase in performance variability. Indeed, although high performance in terms of bouncing error (mean ERR_B) can still be reached, the increase in performance variability can be explained by the loss of ball bouncing stability expected by the model when ACC_V becomes positive. Similarly, the gain of stability expected when ACC_V values are negative can be observed in the small variability of ERR_B performance when ETEL does not exceed 70 ms.

In conclusion, ETEL awareness and perceptuo-motor performance do not overlap. The face validity of a VE system – when users *feel* that the VE depicts the physical movement in “real-time” – does not guarantee the functional validity of that VE. Users’ behaviors may be different in physical and virtual environments, irrespective of the subjective realism and the feeling of *being there* (Stoffregen et al., 2003). In addition, users’ behavioral responses when interacting with VE can be used to measure VE fidelity. For instance, postural responses have been used to measure *presence* (Freeman et al., 2000). An unusual ETEL-related matching between two perceptual modalities in a moving room (Stoffregen et al., 2006) or within a simulator (Stoffregen et al., 2000) can induce significant postural instabilities. In ball bouncing, we have shown evidence here that the exploitation of passive regimes and performance variability are relevant variables for assessing VE fidelity. Thus, ETEL can have dramatic consequences on movement regulation even though ETEL cannot be consciously detected as such. Hence, the careful analysis of action-perception patterns appears necessary to test VE fidelity.

Acknowledgements

Supported by the French *Fond National pour la Science* (IUF 2002:2006) awarded to B. Bardy, and by *Enactive Interfaces*, a network of excellence (IST contract #002114) of the Commission of the European Community, with additional support from the University of Paris Sud 11 (BQR-RV-2003). The authors thank the two anonymous reviewers and Mark Wexler for useful suggestions on the manuscript as well as Bruno Mantel and Jérôme Banal for their respective work on the virtual reality engine.

Appendix A. Predictive filter implementation

The moving average designed for reducing noise in position output operates as follow. For each $i \in [0,N]$, with N, the total number of data to process and T the size of moving average window we computed:

$$f(x_i) = \begin{cases} \text{if } i < T, \quad f(x_i) = \dfrac{\sum_{j=-1/2}^{2i-1/2} x_j}{2i+1} \\ \text{if } i \geq T \quad \text{and} \quad i > N - \dfrac{T}{2}, \quad f(x_i) = \dfrac{\sum_{j=2i-N-1/2}^{N-1/2} x_j}{2(N-i)+1} \\ \text{if } i \geq T \quad \text{and} \quad i \leq N - \dfrac{T}{2}, \quad f(x_i) = \dfrac{\sum_{j=i-N/2}^{i+N/2-1} x_j}{N} \end{cases}$$

A polynomial regression is next performed to reduce ETEL by one sample. On the R first data (given by the moving average), we computed:

$$T_{\text{mean}} = \frac{\sum_{i=0}^{R-1} t_i}{R}$$

t_i was centred ($t_i = t_i - T_{\text{mean}}$). This allows to cancel the latency of moving average computation (Ladiray and Roth, 1987).

The parameters of the polynomial regression (A_z) were then computed by using the R first data, whose t_i were previously centred. The new z values were finally re-calculated thanks to the polynomial regression and $T_{\text{recentred}} = t - \text{delay} - T_{\text{mean}}$ (where t is the current time stamp, prediction is the delay chosen by the experimenter for the prediction (in our case 8.33 ms) and T_{mean} the mean time of the R first data (as previously defined):

$$z = A_{z0} + A_{z1} T_{\text{recentred}} + A_{z2} T_{\text{recentred}}^2 + A_{z3} T_{\text{recentred}}^2$$

References

Adams JL. An investigation of the effects of the time lag due to long transmission distances upon remote control, phase I-tracking experiments. NASA Technical note D1211. 1961.

Adelstein BD, Johnston ER, Ellis SR. Dynamic response of electromagnetic spatial displacement trackers. Presence Teleoper Virtual Environ 1996;5:302–18.

Adelstein BD, Lee TG, Ellis SR. Head tracking latency in virtual environments: psychophysics and a model. In: Proceedings of the Human Factors and Ergonomics Society (47th Annual Meeting); 2003. p. 2083–7.

Allison RS, Harris LR, Jenkin M, Jasiobedzka U, Zacher JE. Tolerance of temporal delay in virtual environments. In: Proceedings of the 2001 IEEE Virtual Reality Conference (VR’01); 2001. p. 247–53.

Barfield W, Hendrix C, Bjorneseth O, Kaczmarek K, Lotens W. Comparison of human sensory capabilities with technical specifications of virtual environment equipment. Presence Teleoper Virtual Environ 1994;4:329–56.

Beall AC, Loomis JM, Philbeck JM, Fikes TJ. Absolute motion parallax weakly determines visual scale in real and virtual environments. In: Proceedings of Conference on Human Vision, Visual Processing, and Digital Display (SPIE Vol. 2411); 1995. p. 288–97.

Brooks F. What's real about virtual reality? In: Proceedings of the IEEE Computer Graphics and Applications; 1999. p. 16–27.

Bryson S. Effects of lag and frame rate on various tracking tasks. In: Proceedings of the SPIE—The international society for optical engineering; 1993. p. 155–66.

Bryson S, Fisher SS. Defining, modeling and measuring system lag in virtual environments. In: Proceedings of the SPIE—The international society for optical engineering; 1990. p. 98–109.

Couroussé D, Jansson G, Florens JL, Luciani A. Visual and haptic perception of object elasticity in a squeezing virtual event. In: Proceedings of the EuroHaptics 2006 Conference; 2006. p. 283–8.

Cunningham DW, Billock VA, Tsou BH. Sensorimotor adaptation to violations of temporal contiguity. Psychol Sci 2001a;12:532–5.

Cunningham DW, Chatziastros A, von der HM, Bulthoff HH. Driving in the future: temporal visuomotor adaptation and generalization. J Vis 2001b;1:88–98.

Day PN, O'Brian Holt P, Russel GT. Modelling the effects of delayed visual feedback in real-time operator control loops: cognitive perspective. In: Proceedings of the XVIII European Annual Conference on Human Decision Making and Manual Control; 1999. p. 70–9.

de Rugy A, Wei K, Muller H, Sternad D. Actively tracking 'passive' stability in a ball bouncing task. Brain Res 2003;982:64–78.

Dijkstra TMH, Katsumata H, de Rugy A, Sternad D. The dialogue between data and model: Passive stability and relaxation behavior in a ball bouncing task. J Nonlinear Sci 2004;11:319–44.

Ellis SR, Young MJ, Erlich SM. Discrimination of changes of latency during voluntary hand movement of virtual objects. In: Proceedings of the Human Factors and Ergonomics Society; 1999a. p. 1182–6.

Ellis SR, Adelstein BD, Baumeler S, Jense GJ, Jacoby RH. Sensor spatial distorsion, visual latency, and update rate effects on 3D tracking in virtual environments. In: Proceedings of the IEEE Virtual Reality 1999 Conference (VR'99); 1999b. p. 218–21.

Ellis SR, Young MJ, Ehrlich SM, Adelstein BD. Discrimination of changes in latency during head movement. In: Proceedings of the 8th International Conference on Human-Computer Interaction (HCI'99); 1999c. p. 1129–33.

Ferrell WR. Remote manipulative control with transmission delay. Percept Motor Skills 1963;20:1070–2.

Flynn SB. The perception of relative mass in physical collisions. Ecol Psychol 1994;6:185–204.

Foulkes AJ, Miall RC. Adaptation to visual feedback delays in a human manual tracking task. Exp Brain Res 2000;131:101–10.

Franck N, Farrer C, Georgieff N, Marie-Cardine M, Dalery J, d'Amato T, et al. Defective recognition of one's own actions in patients with schizophrenia. Am J Psychiatry 2001;158:454–9.

Freeman J, Avons SE, Meddis R, Pearson DE, Ijsselsteijn WA. Using behavioral realism to estimate presence: a study of the utility of postural responses to motion-stimuli. Presence Teleoper Virtual Environ 2000;9:149–64.

Garret AL. Reduction of latency in virtual environment applications. 2002. Masters Thesis. Jacksonville State University, MCIS department, Jacksonville, AL.

Gauthier GM, Vercher JL. Visual vestibular interaction: vestibulo-ocular reflex suppression with head-fixed target fixation. Exp Brain Res 1990;81:150–60.

Gescheider GA. Psychophysics: the fundamentals. Hillsdale, NJ: Lawrence Erlbaum Associates; 1997.

He D, Liu F, Pape D, Dawe G, Sandin D. Video-based measurement of system latency. In: Proceedings of the 4th International Immersive projection Technology Workshop (IPT 2000); 2000.

Jung JY, Adelstein BD, Ellis SR. Discriminability of prediction artifacts in a time-delayed virtual environment. In: Proceedings of the 44th Annual Meeting of the Human Factors and Ergonomics Society (IEA 2000/HFES 2000); 2000. p. 499–502.

Klatzky RL, Loomis JM, Beall AC, Chance SS, Golledge RG. Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. Psychol Sci 1998;9:293–8.

Korteling JE, Sluimer RR. A critical review of validation methods for the man-in-the-loop simulators. TNO Human Factors Research Institute, Kampweg 5 3769 DE. TNO-report TM-99-A023, 1-31. 16-3-1999. Soesterberg.

Korteling JE, Van den Bosch K, Van Emmerik ML. Low-cost simulators 1a: literature review, analysis of military training, and selection of task donamins. The Netherlands: TNO Human Factors Research Institute. TNO-report TM-97-A035 1997, Soesterberg.

Ladiray D, Roth N. Lissage robuste de séries chronologiques. Une étude expérimentale. Annales d'économie et de statistique 1987;5:147–81.

Lapointe JF, Vinson NG. Effects of joystick mapping and field-of-view on human performance in virtual walkthroughs. In: Proceedings of the 1st International Symposium on 3D Data Processing Visualization and Transmission; 2002. p. 490–3.

Leube DT, Knoblich G, Erb M, Grodd W, Bartels M, Kircher TT. The neural correlates of perceiving one's own movements. Neuroimage 2003;20:2084–90.

Loomis JM, Blascovich JJ, Beall AC. Immersive virtual environment technology as a basic research tool in psychology. Behav Res Methods Instrum Comput 1999;31:557–64.

Miall RC, Jackson JK. Adaptation to visual feedback delays in manual tracking: evidence against the Smith Predictor model of human visually guided action. Exp Brain Res 2006;172:77–84.

Miall RC, Weir DJ, Stein JF. Visuomotor tracking with delayed visual feedback. Neuroscience 1985;16:511–20.

Miller D, Bishop D. Latency meter: a device for easily monitoring VE delay. In: Proceedings of SPIE Stereoscopic Displays and Virtual Reality Systems IX; 2002. p. 458–64.

Mine MR. Characterization of end-to-end delays in head-mounted display systems. TR93-001. 23-3-1993. University of North Carolina at Chapel Hill, Department of Computer Science.

Mirtich B. Impulse based dynamic simulation of rigid body systems. 1996. PhD thesis, University of California, Berkeley.

Mirtich B. Timewarp rigid body simulation. In: Proceedings of the 27th International Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '00); 2000. p. 193–200.

Morice AH, Siegler IA, Bardy BG, Warren WH. Learning new perception-action solutions in virtual ball bouncing. Exp Brain Res 2007;181:249–65.

Moroney WF, Moroney BW. Simulation. In: Garland DJ, Wise JA, Hopkins VD, editors. Human factors in aviation systems. Hillsdale: Lawrence Erlbaum Associates I; 1998, 358–388.

Nusseck M, Lagarde J, Bardy BG, Fleming R, Bulthoff HH. Perception and prediction of simple object interactions. In: Proceedings of the 4th symposium on Applied perception in graphics and visualization (APGV '07); 2007. p. 27–34.

O'Sullivan C, Dingliana J. Collisions and perception. In: Proceedings of the 28th International Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '01); 2001. p. 151–68.

O'Sullivan C, Dingliana J, Giang T, Kaiser MK. Evaluating the visual fidelity of physically based animations. In: Proceedings of the 30th International Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '03); 2003. p. 527–36.

Peruch P, Gaunet F. Virtual environments as a promising tool for investigating human spatial cognition. Cah Psychol Cogn 1998;17:881–99.

Peruch P, Vercher JL, Gauthier GM. Acquisition of spatial knowledge through visual exploration of simulated environments. Ecol Psychol 1995;7:1–20.

Peruch P, May M, Wartenberg F. Homing in virtual environments: effects of field of view and path layout. Perception 1997;26:301–11.

Regan MJP, Miller GSP, Rubin SM, Kogelnik C. A real-time low-latency hardware light-field renderer. In: Proceedings of the 26th International Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99); 1999. p. 287–90.

Riccio GE. Coordination of postural control and vehicular control: Implications for multimodal perception and simulation of self-motion. In Hancock FC&VE, editor. *Local applications of the ecologial approach to human-machine systems*. Hillsdale, NJ: Lawrence Erlbaum Associates: 1995; 122–81.

Runeson S, Vedeler D. The indispensability of precollision kinematics in the visual perception of relative mass. Percept Psychophys 1993;53:617–32.

Schaal S, Atkeson CG, Sternad D. One-handed juggling: a dynamical approach to a rhythmic movement task. J Mot Behav 1996;28:165–83.

Sheridan TB. Musings on telepresence and virtual presence. Presence Teleoper Virtual Environ 1992;1:120–3.

Sheridan TB, Zeltzer D. Virtual environments. MD Comput 1994;11:307–10.

Slater M. Measuring presence: a reponse to the witmer and singer presence questionnaire. Presence Teleoper Virtual Environ 1999;8:560–5.

Slater M, Usoh M. Presence in immersive virtual environments. In: Proceedings of the IEEE conference—Virtual reality Annual international Symposium; 1993. p. 90–6.

Smith KU, Smith WM. Perception and action. Philadelphia: Saunders; 1962, 247–77.

Stanney KM, Mourant RR, Kennedy RS. Human factors issues in virtual environments: a review of the literature. Presence Teleoper Virtual Environ 1998;7:327–51.

Sternad D, Duarte M, Katsumata H, Schaal S. Bouncing a ball: tuning into dynamic stability. J Exp Psychol Hum Percept Perform 2001;27:1163–84.

Stoffregen TA, Hettinger LJ, Haas MW, Roe MM, Smart LJ. Postural instability and motion sickness in a fixed-based flight simulator. Hum Factors 2000;42:458–69.

Stoffregen TA, Bardy BG, Smart LJ, Pagulayan RJ. On the nature and evaluation of fidelity in virtual environments. In: Hettinger LJ, Haas MW, editors. Virtual and adaptative environments: applications, implications, and human performance issues. Mahwah, NJ: Lawrence Erlbaum; 2003. p. 111–28.

Stoffregen TA, Hove P, Schmit J, Bardy BG. Voluntary and involuntary postural responses to imposed optic flow. Motor Control 2006;10:24–33.

Tarr MJ, Warren WH. Virtual reality in behavioral neuroscience and beyond. Nat Neurosci 2002;5(Suppl):1089–92.

Todd JT, Warren Jr WH. Visual perception of relative mass in dynamic events. Perception 1982;11:325–35.

Vercher JL, Gauthier GM. Eye-head movement coordination: vestibulo-occular reflex suppression with head-fixed target fixation. J Vestibul Res 1990/91;1:161–70.

Warren WH, Kim EE, Husney R. The way the ball bounces: visual and auditory perception of elasticity and control of the bounce pass. Perception 1987;16:309–36.

Watson B, Spaulding V, Walker N, Ribarsky W. Evaluation of the effects of frame time variation on VR task performance. In: Proceedings of the 1997 Virtual Reality Annual International Symposium (VRAIS '97); 1997. p. 38.

Welch RB. Perceptual modification: adpating to virtual environment. New York: Academic Press; 1978.

Wells MJ, Venturino M. Performance and head movements using a helmet-mounted display with different sized fields-of-view. Opt Eng 1990;29(8): 870–7.

Wildzunas RM, Barron TL, Wiley RW. Visual display delay effects on pilot performance. Aviat Space Environ Med 1996;67:214–21.

Witmer BG, Singer MJ. Measuring presence in virtual environments: a presence questionnaire. Presence Teleoper Virtual Environ 1998;7:225–40.