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Keyword	Proposer	Short definition (if necessary)
PSE – Point of Subjective Equality	Damien Couroussé, INPG	Only available for the two alternative forced choice technique The latency difference that is detected 50% of time when actually present in two alternative forced choice situation is the point of subjective equality (PSE).
JND – Just Noticeable Difference	Damien Couroussé, INPG	Only available for the two alternative forced choice technique: The change in latency required to increase or decrease detection 25% from the PSE is the just noticeable difference (JND) (in Ellis & al, 2004).

Temporal delays in action-vision loop
©Damien Couroussé
September 9th, 2004

When one speaks about latency or time delay in VE or teleoperation, it usually refers to the period of time from input action to visual display. This is one of the main technological bottlenecks since it deals with incompressible time delays due to the processing of data coming from tracking systems, the processing of data that have to be delivered back, and the displaying of these new data.

The study of the human perception of time delays falls within many areas. It is of first interest for the psychophysics, but also for fields where the technological design has a direct impact on human behavior, such as teleoperation, immersive and non-immersive VE, training simulators, etc. Moreover, the study of human perception of time delays is of prime interest for VE designers, since the cost of time required for data processing is one of the main bottlenecks.

The following article review mainly deals with VE systems, where the user's movements of both head and hands are visually displayed in real-time. Studies of time delay perception in VE commonly proceed as follow: the subject is equipped with a visual head mounted display, which provides him or her a stereoscopic view of the virtual scene. A tracking system gives head and hands position and orientation, and allows integrating the user in the virtual scene. Thus, display of the virtual scene depends on the position and the orientation of the user's head.

Usual tracking systems provide refresh rates of 60 or 120Hz, and the minimum overall full latency of the full system is about 30ms – Adelstein & al (2003) report a minimum overall latency in their system 33±5ms, Ellis & al (1999) report 27±5ms; Ware and Balakrishnan (1994) present a head lag of 114ms, and a hand lag of 87ms. Ellis & al (2004) system ensures a base latency of 10,4ms at a tracking refresh rate of 60Hz.

The literature on manual control has long established that latency in displays or controls has a major negative impact on performance (Sheridan & Ferrel, 1963, Sheridan, 1992). Overall latency in visual display is a barrier to perceived image stability, drastically weakens the quality of performance, causes diseases such as disorientation and cybersickness –or as known as simulator sickness (Frank & al 1988, Allison & al 2001)– and impedes the subjective sense of presence. Lags in hand movements can degrade performance in grasping or pointing tasks, and lags in head movements can generate apparent motion of objects or space where they are still. Adelstein & al (2003) report this phenomenon as “image slip”, which they define as “the virtual scene’s artifactual concomitant motion with the observer’s head resulting from time lag”.

Richard & al (1996 – quoting Wloka, 1995) report that the “high ceil” of time delays threshold for control is about 300ms, above which the user loses the immersive feeling in the simulation and modifies his control strategy from continuous regulation to a “move and wait” strategy. Under this “high ceil” for time delay, continuous control remains possible and delay do not interfere so much with the user, but it still has an effect on the quality of performance and might be perceived by the user.

It has long been believed that the human perception of lag would match up with Weber’s law, i.e. that the amount of perceived variation of delay would be a ratio of the base latency of the system[1]. First studies report results that go along with Weber’s law: Watson & al (1997) report that (symmetrical) deviations of lag up to 40% do not affect task performance in the range of frame time commonly accepted in VE (50ms or 20fps). However, as the frame rate falls (frame time of 100ms or more, 10fps), the amount of fluctuation interacts significantly with the performance (placement time).

Human processing time:

One part of the studies in this domain tries to give an evaluation of the human processing time (from action to vision). The process by which an evaluation of the human processing time is provided is based on the Fitts’ law (Ware and Balakrishnan, 1994).

The Fitts’ paradigm describes the time taken to acquire a visual target with a hand or arm movement. The most commonly used formula is applied to movements performed along one dimension or to movements that can be reduced along an axis:

$MeanTime = C_1 + C_2 \log_2(\frac{D}{W} + 1.0)$, where:

- D is the distance from the end of the movement to the center of the target
- W is the target width
- C_1 and C_2 are experimentally determined constants. $1/C_2$ is also defined as the index of performance [bit.s^{-1}], and ID is defined as: $ID = \log_2(\frac{D}{W} + 1.0)$

The process modeled by Fitts is a series of movements each of which gets the hand-guided probe closer to the target, until the probe falls within the target area. However, as the hand does not come to a complete stop in reaching movements, a series of corrections are applied

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[1] Ernst Weber was the first to describe the difference threshold mathematically. Weber's law can be stated as follows: for any particular sensory system, the ratio of the difference in stimulation divided by the original stimulation is a constant. Different sensory systems have different constants.

$$\frac{\Delta I}{I} = K$$

Weber's Law, more simply stated, says that the size of the *just noticeable difference* (i.e., *delta I*) is a constant proportion of the original stimulus value.

in a dynamic feedback loop. Thus, the model of Fitts provides a good accuracy for a mean time evaluation.

In order to introduce machine-processing lags, Ware and Balakrishnan propose the following formula, still for movements performed along one direction:
$MeanTime = C_1 + C_2(C_3 + MachineLag)ID$, where:

- C_1 represents the sum of the initial response time and the time required to confirm the acquisition of the target.
- C_2ID represents the average number of iterations of the control loop
- C_3 is the human processing time to make a corrective movement
- *MachineLag* is the machine processing time (i.e. the delay introduced by the machine)

Human sensibility to overall latency:

In three experiments, by comparing head and hand movements in base conditions (i.e. with the base latency provided by the system) and in four other conditions where supplementary lags are added independently to head or hand movements, Ware and Balakrishnan provide an estimation of the human processing time of 166ms (C_3). Therefore, they show that in the specific proposed task there is no significant effect of increased lags applied to head movements, and that frame rates below 15Hz drastically increase the mean response time. These results are consistent with previous estimates provided by the literature (Carleton 1981, Keele and Posner 1968, quoted by Ware and Balakrishnan), which are given between 100 and 200ms.

In an other study based on the Fitts' paradigm, Ware and MacKenzie (1993), still on the study of a target acquisition task, show that lag has effects on movement time, error rate, and bandwidth (bits/s) as the value becomes greater or equal to 75ms. Lags of 8.3 and 25 ms induce quite the same results on the overall performance, and therefore do not seem to perturb hand movements.

Discrimination of changes in latency

Another way to approach the human sensibility to time delay is to determine how much is the human perceptive to *variations* of latency. Ellis & al (1999) had subjects comparing a reference situation, of which latency was equal to the minimal full system latency of 27±5ms or was fixed to 97 or 196ms, with a test situation, in which several latency increments of 16.7ms were added. The subjects were asked to discriminate between the reference situation and a test situation, by observing a virtual scene composed of a ball of 10cm diameter, while moving the head back and forth.
The results show that the discrimination of latency does not follow the Weber's law: JND[2] seems indeed to be roughly independent of the base latency introduced.
Therefore, the authors recommend designers of VE environments to avoid important variations of latencies, even if the base latency is important: users of long latency VE systems will be as sensitive to changes in latency as those who use prompter systems.

In another study, still based on the comparison of a base reference situation to a test situation, in which supplementary latency is added, Adelstein & al (2003) show that the average JND is

[2] The latency difference which is detected 50% of time when actually present in two alternative forced choice situation is the point of subjective equality (PSE).
The change in latency required to increase or decrease detection 25% from the PSE is the just noticeable difference (JND) (in Ellis & al, 2004).

about 17ms, and that the mean PSE is about 50ms, whatever the duration of the base latency (33, 100 or 200ms) is. The explanation proposed is that the perception of delays in VE might be due in part to “image slip”, which is the apparent movement of the image as a consequence of head tracking latency, or as defined by Adelstein & al “the virtual scene’s artifactual concomitant motion with the observer’s head resulting from time lag”. Therefore, as the subject moves his head in a sinusoidal movement, for certain sinusoidal motion frequencies, the amount of added incremental delay produces the same proportions of image slip in displacement, regardless of the base latency. This could explain in part why the results are not according to Weber’s law.

Ellis & al (2004) confirmed these results. They found JND about 10-15ms, and PSE about 30ms, for a system where the base latency was only of 10.4ms. The aim of the study was to determine if the perception of latency was depending on the complexity of the visual scene or not. It was shown that three different visual scenes, one with a single object displayed in foreground with a black background (i.e. no background), one with of a single background (interleaved staircases) without foreground, and the last with both a foreground object and a background, provided no difference on the results. In a further experiment (to be published), the authors shown that latency discrimination is not depending on the complexity of the visual scene.

Adaptation to temporal latency

The problems of spatial and temporal misalignment between sensorialities cause diseases to the users of VE and impair overall performance. However, it has been long shown that a short learning stage of a few minutes permits human to adapt to spatial misalignment between sensorialities (this is the case study of *prism adaptation*). After this recalibration, the spatial misalignment does not impair performance anymore, nor is even felt as disturbing. Cunningham and al. (2001) studied the case of temporal misalignment in a driving task without force feedback, and shown that the subjects managed to adapt to a temporal delay of 250ms, after a training period had been performed. However, after training to temporal delay, a negative *aftereffect*[i] was observed when the temporal delay removed or set to its minimum value (35ms – this minimum value was said not to be noticed by the subjects). Therefore, the error rates drastically increased and gave similarly results to a performance of the delayed task without training. In another study, Cunnigham et al. (2000) report that, if the subjects complained at first about the delay, they did not noticed it after some training, and even improved their performance compared to the pre-test, which was measured with a 35ms delay. Several subjects “spontaneously reported that, toward the end of training, the visual and proprioceptive feedback seemed simultaneous”. The authors furthermore add that the subject’s perception of latency was modified such that “when the delay was removed, the plane seemed to move before the mouse did”.

Bürki-Cohen and al. (1996) established a review of comparative studies between full flight simulators and fixed-based simulators. Fisex-based simulators only differ from full flight simulators in all respects except for absence of platform motion. Quoting Levison & Junker (1977), they reported that large reductions of mean-squared error were observed in a tracking task, in all conditions of delay (no delay, 80, 200 and 300ms). The group submitted to the 200 and 300 ms of time delay was however exposed to some aftereffects. For that reason, the authors to be avoid motion platform in flight simulators if the time delay could not be minimized, since they stated that badly synchronized motion is in fact worse than no motion at all.

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Cunningham, Douglas W., Biillock, Vincent A., Tsou, Brian H. (2001). Sensorimotor Adaptation to Violations of Temporal contiguity, *Psychological Science,* Volume 12: Issue 6

Ellis, Stephen R., Mania, Katerina, Adelstein, Bernard D. and Hill, Micheal, (2004). Generalizeability of latency detection in a variety of virtual environments, *Human Factors and Ergonomics Society, 48th Annual Meeting, New Orleans, USA (to appear)*

Ellis, Stephen R., Young, Mark J. and Adelstein, Bernard D. (1999). Discrimination of changes in latency during head movement, *Proceedings of Computer Human Interfaces, pp. 1129-1133*

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Richard, P., Birebent, G., Coiffet, P., (1996). Effect of frame rate and force feedback on virtual object manipulation, *Presence, Vol. 5, No. 1, 95-108*

Richard, Paul, Birebent, Georges, Coiffet, Philippe, Burdea, Grigore, Gomez, Daniel, Langrana, Noshir (1996). Effect of Frame Rate and Force feedback on Virtual Object Manipulation *Presence, Vol 5, No. 1, 95-108.*

Stanney, Kay M., Mourant, Ronald R., Kennedy, Robert S., (1998). Human Factors Issues in Virtual Environments: A Review of the Literature, *Presence, Vol 4, No. 4, pp. 327-351*

Ware, Colin, and Balakrishnan, Ravin, (1994). Reaching for Objects in VR Displays: Lag and Frame Rate, *ACM Transactins on Computer-Human Interaction, Vol 1, No 4, pp. 331-356.*

L. James Smart, Jr., Miami University, Oxford, Ohio, Thomas A. Stoffregen, University of Minnesota, Minneapolis, Minnesota, and Benoît G. Bardy, University of Paris Sud XI, Orsay, France: Visually Induced Motion Sickness Predicted by Postural Instability, *HUMAN FACTORS*, Vol. 44, No. 3, Fall 2002.

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Commented references in temporal delay in action-vision loop

Adelstein, Bernard D., Thomas, G. L., Ellis, Stephen R.* (2003). Head tracking latency in virtual environments: psychophysics and a model, *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting.

The authors of this paper presents some experiments that tend to quantify the human perception of latency, and to describe the mechanism by which the latency is perceived. The field of investigation is the immersive VE, in which the user is equipped with a head-mounted display for stereo rendering of scenes, and a head tracking system in order to display the scene depending of the position of the user's head.
One of the main ideas presented here, is that the perception of delays might be due in part by "image slip", which is the apparent movement of the image as a consequence of head tracking latency, or as defined by Adelstein & al "the virtual scene's artifactual concomitant motion with the observer's head resulting from time lag".
Subjects are asked to move their heads "smoothly and sinusoidally" in a yaw movement from side-to-side. Latency conditions are presented in sequential pairs composed of a reference and a probe level, which is made of the reference level latency plus an added latency. Reference levels of latency are either 33, 100 or 200ms. Subjects have to decide if the intervals of the reference and of the probe level differ or not.
The methods used are a combination of the staircase method (Method of Limits) with randomized series. The results are discussed for *added latency*, and show that the average Just Noticeable Difference is about 17ms, and the mean Point of Subjective Equality is about 50ms. At last, JND and PSE results are not significantly varying depending on the reference level of latency.

Crowley, James L., Coutaz, Joëlle, Bérard, François (2000). Things That See, *Communications of the ACM 43, 3, pp 54-64, ACM Press New York, NY, USA.*

This paper focuses on the techniques used in HCI that bring together human gesture and machine vision, which is defined as the observation of an environment using cameras. The main advantage of machine vision for HCI is that the user doesn't need any tool; this means that human actions can be tracked without being constrained.
In that kind of interaction environment, this article particularly specifies that "the latency of machine perception must be less than 50ms for direct manipulation using finger tracking".

Cunningham, Douglas W., Chatziastros, Astros, von der Heyde, Markus, Bülthoff, Heinrich H. (2000). Temporal Adaptation and the role of temporal contiguity in spatial behavior, *Technical Report No. 85*, MPI, December 2000

It has now long been established that humans are sensitive to spatial misalignment relationships between sensorialities (study of *prism adaptation*), but that after a few minutes of recalibration, this misalignment does not impair performance anymore, nor is even felt as disturbing. This kind of adjustment is known as Spatial Adaptation.
This paper addresses the similar problem of alignment between sensorialities in the temporal dimension. Although no compensation effects were noticed for temporal delays between the different sensorialities, a previous experiment has shown an adaptation to intersensory temporal discrepancy after long learning (Cunningham et al. 2001), and the experiments presented some adaptation to temporal delays. As in the case of spatial misalignment, an aftereffect is noticed in the two experiments presented here: learning to perform the task with temporal delay greatly reduces the performance with no time delay afterwards.
At last, the second experiment is processed in order to reduce the simulator sickness felt by some subjects. One subject still experienced simulator sickness, but the decrease of the proportion of affected subjects might show that temporal delay is not an increasing factor of simulator sickness, which could only be due to a conflict between the visual and vestibular perception of acceleration.

Cunningham, Douglas W., Biillock, Vincent A., Tsou, Brian H. (2001). Sensorimotor Adaptation to Violations of Temporal contiguity, *Psychological Science,* Volume 12: Issue 6

The perception of one event that is addressed to different sensorialities is unique, despite the fact that the different sensorialities are processed at different speeds, and that neurons may respond with different latencies to an identical stimuli. This suggests that the brain is able to process the different modalities by compensating the time variations among the stimuli.

The experiment proposed here shows that in a guidance task, where a displayed airplane is controlled by mouse movements (no force feedback), the subjects perform adaptation to an added time delay (235ms) and performed the task as well in presence of such a delay compared to the task with no delay. The time delay was at first said to be disturbing and subjects complained about it. However, it is shown that training to time delays has strong negative aftereffects: after training, the subjects are no more able to perform the task with an unnoticeable delay (35ms).

Ellis, Stephen R., Mania, Katerina, Adelstein, Bernard D. and Hill, Micheal, (2004). Generalizeability of latency detection in a variety of virtual environments, *Human Factors and Ergonomics Society, 48th Annual Meeting, New Orleans, USA (to appear)*

This study deals with the discrimination of latency changes in VE during head movement.

Before the experiment, subjects are carefully instructed about the effects of latency on the display of the visual scene. The equipment is composed of a head-mounted display and a tracking system for head and hand movements. In the three experiments presented, subjects are asked to detect latencies introduced in the display of a virtual scene. The virtual scene is composed either of a single object displayed in foreground with a black background (i.e. no background), either of a single background without foreground, or both a foreground object and a background. Subjects are then asked to compare a reference situation, which present a base latency of 10.4ms, to a test situation, in which supplementary steps of 8.5ms delay are added to the reference latency.

The results confirm previous studies conducted with somewhat different psychophysical techniques and very different viewing techniques: the JND is about 10-15ms, and PSE is about 30ms. These thresholds are a bit smaller than those presented in similar experiments, and authors expect this to be due to the fact that subjects were instructed about effects of delay. Therefore, the authors recommend designers of VE environments to avoid important variations of latencies (below 16ms), even if the base latency is important.
Furthermore, latency discrimination is shown not to be depending on the complexity of the environment (i.e. the combination or existence of foreground and background). In a further experiment (to be published), the authors show that latency discrimination is not depending on the complexity of the displayed scene.

Ellis, Stephen R., Young, Mark J. and Adelstein, Bernard D. (1999). Discrimination of changes in latency during head movement, *Proceedings of Computer Human Interfaces, pp. 1129-1133*

When the latency exceeds 300ms in VE, the user is said to adopt a "move and wait" strategy, but the thresholds for first effects of short latencies remain imprecisely known. This paper focuses on the discrimination of latency changes in VE during head movement.
In the experiment presented here, subjects are asked to compare a reference situation, which presents base latencies of are 27, 97 or 196 ms, to a test situation, in which a supplementary delay is added to the reference latency.
The results show that the discrimination of latency does not follow the Weber's law: JND seems indeed to be roughly independent of the base latency introduced. Therefore, the authors recommend designers of VE environments to avoid important variations of latencies, even if the base latency is important.

Richard, Paul, Birebent, Georges, Coiffet, Philippe, Burdea, Grigore, Gomez, Daniel, Langrana, Noshir (1996). Effect of Frame Rate and Force feedback on Virtual Object Manipulation *Presence, Vol 5, No. 1, 95-108.*

This paper deals with the effects of frame rate (graphics refresh rate) and viewing mode on the user performance in Immersive Virtual Environment.
Two experimental studies are done. In the first one, users are asked to grasp as quick as possible a virtual ball, which is moving relatively fast in random directions. In the second one, the subjects are asked to reach and pick up a virtual ball along a determined path (which is materialized by the vertical projection of the ball between two lines on the ground), while applying a low but stable amount of deformation on the ball, and achieving the task in less than 15 sec.
Results show that:

- High frame rates and stereoscopic view require less adaptation from the user, since these conditions are said to be closer to the natural conditions in which a human interacts with its environment.
- Completion times and efficiency are worse as the frame rate falls below 14 fps.
- Redundant information (for instance information about force feedback applied to the user on visual or auditory modalities) improve the completion time and reduce the task error, especially in the case of redundant information by auditory cues.

Stanney, Kay M., Mourant, Ronald R., Kennedy, Robert S., (1998). Human Factors Issues in Virtual Environments: A Review of the Literature, ***Presence, Vol 4, No. 4, pp. 327-351***

While the number of studies and applications using techniques coming from the Virtual Realities is still growing up, the knowledge about human factors related to these new uses of technology remains quite poor. This paper thus provides an overview of many of the human-factor issues related to VR. Starting with the question of efficiency and performance of applications using VR techniques, the authors present the current issues in increasing the degree of presence and effectiveness of VEs. These factors are then related to tasks characteristics and user characteristics (including a short review of human sensory capabilities in the visual, auditory and haptic fields). The two last sections of this paper deal with health and safety issues in VE (including review of knowledge about cybersickness effects and diseases or injuries by displays) and social implications.

Ware, Colin, and Balakrishnan, Ravin, (1994). Reaching for Objects in VR Displays: Lag and Frame Rate, ***ACM Transactins on Computer-Human Interaction, Vol 1, No 4, pp. 331-356.***

This paper presents three experiments verifying the previous results about human perception of time delays. According to the law of Fitt, the mean time necessary for a reaching task is depending on the size of the target, and psychophysical constants depending on the motor and cognitive capacities of the subject. The authors propose slight modifications of this law in order to take into account the delays introduced by the data processing and display time in VE.

Frank, L. H., Casali, J. G., & Wirewill, W. (1988). Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. ***Human Factors, 30,*** **201-217**

L. James Smart, Jr., Miami University, Oxford, Ohio, Thomas A. Stoffregen, University of Minnesota, Minneapolis, Minnesota, and Benoît G. Bardy, University of Paris Sud XI, Orsay, France: Visually Induced Motion Sickness Predicted by Postural Instability, ***HUMAN FACTORS*****, Vol. 44, No. 3, Fall 2002.**

Studies performed in the 10 past years report that motion sickness may be correlated with the perception of vection, which is defined by the authors as the *experience of self-motion relative to the inertial environment*.
The present study tries to provide qualitative and quantitative measures in order to predict motion sickness. In the experiment, standing up subjects are placed in a moving room, which exposes them to a visual stimulus, and which one is supposed to induce the feeling of vection to the participants. The results show that the subjects who more experienced motion sickness more often reported the feeling of motion. Furthermore, it is shown that postural instability precedes motion sickness.

Watson, B., Spaulding, V., Walker, N., Ribarsky, W. (1997) Evaluation of the Effects of Frame Time Variation on VR Task Performance, ***VRAIS ’97, IEEE Virtual Reality Annual Symposium, 38-44***

The presented study tries to show the effects of lag fluctuation over time in VE.

The proposed task is the combination of two ones: (1) the grab of a moving target (open loop task, i.e. movements that do not allow feedback or correction), and (2) the placement of the grabbed target on a pedestal (closed loop task, i.e. movements that are continuously corrected with the help of feedback information in order to reach a goal). In the proposed task, the frame delay continuously changes during the movement according to a sinusoidal law of variation.

MacKenzie, I.S., Ware, C. (1993). Lag as determinant of human performance in interactive systems. ***Proceedings of the ACM Conference on Human Factors in Computing Systems – INTERCHI'93,*** **488-493. New-York:ACM.**

The sources of lag (the delay between input action and output response) and its effects on human performance are discussed. The authors measured the effects of time delay in a study of target acquisition using the Fitts' law paradigm with the addition of four lag conditions. The results show that lag is xxx on movement as its value becomes greater or equal to 75ms.

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[i] The aftereffect is the fact that the adaptation to an intersensory discrepancy reduces a subject's ability to accurately perform the task once the time delay is removed: the benefits of training are gone or reversed.