Generalizeability of latency detection in a variety of virtual environments

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User perceptual sensitivity to changes of full system latency was tested in three simple virtual environments, two with either only a foreground or a background object and an additional one that combined both types. Earlier psychophysical measurements of sensitivity (just noticeable differences) and bias (points of subjective equality) are confirmed and contrasted with other reports in which subjects may not have been sufficiently instructed as to what the visual consequences of latency were. A possible explanation of these dif-ferences could have been related to a visual capture effect reported initially by Matin. This possibility is discounted by precise measures of bias and sensitivity in 13 subjects. Results based on rigorous psychophysical measurements support earlier claims that per-ceptual stability within a variety of virtual environments will require latencies less than 16 ms.

Proposal:

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Summary

Introduction

Excessive system latency is a well-known defect of common virtual environment (VE) and teleoperation systems. It is particularly troublesome for head tracked systems since delays in head orientation measurement give rise to errors in presented visual direction. But it is doubly confusing for hand-held virtual objects because the reversed error signs for hand and head tracked elements result in spurious movement to which users have difficulty adapting (Smith, McCrary & Smith, 1962). Depending upon the amount of error and the users specific behavior, these dynamic registration errors can lead to visual instability and can degrade performance and simulation fidelity (Ellis, Bréant, Menges, Jacoby & Adelstein, 1997). In severe cases they can lead to disorientation and/or “simulator sickness” making the use of a VE problematic

(Frank, Casali, & Wierwilli, 1988). Visual motor performance is also well-known to be degraded by transport lag (Ferrell & Sheridan, 1963), the type of latency we have studied in virtual environment systems.

Latency in VEs has consequently be been the object of measurement, software or hardware optimization (Regan, Miller, Rubin & Kogelnik, 1999) and user studies to assess its perceptual and performance impacts. Because latency is unavoidable in some systems such as space teleoperation over long distances, purely software or hardware techniques cannot remove it totally from real time operation. Techniques for managing it, thus, necessarily must be informed by user studies of its performance and perceptual impact.

Earlier studies have examined overall user performance (e.g., Ellis, et al, 1997; Watson, Walker, Woytiuk & Ribarsky, 2003), some have investigated user's ability to detect latency during hand motion of virtual objects (Ellis et al, 1999a. Others have investigated user sensitivities to latency changes during head rotations (Ellis, et al, 1999b; Regan et al, 1999). Many of these studies suggest that representative user sensitivity to latency change is quite low with latency difference becoming noted with differences on the order of 10-20 ms. These studies show also that the latency discrimination process does not exhibit Weber's Law, that it cannot be based on a purely temporal judgement, and that it depends to at least some degree upon image slip during movement (Adelstein, Lee & Ellis, 2003).

A recent study, however, reports that a much larger value of latency is required for its effects to become visible during head rotation. This report from Allison et al (2001) suggests that visual instability due to system latency during periodic head movements is not apparent at a 50% level (i.e. PSE /bias) until latencies are on the order of 200 msec. It conflicts with measurements made in our laboratory that indicate user sensitivity to latency to be much more acute during similar head rotations. Though there are many possible technical differences in apparatus and psychophysical technique between the studies in our two laboratories, our environments should have had at least similar visual quality since we used the same V8 head mounted display (HMD).

One major difference, however, is that in prior studies (Ellis et al., 1999ab; Adelstein et al., 2003) we have asked our subjects to compare the apparent stability of two instances of system latency while viewing a foreground virtual object presented against a black background. In contrast, Allison et al.'s subjects judged the visual stability of a patterned background surface alone against their internal sense of what constituted stability. Allison et al. measured only their observer's bias (PSE) [1], while in Adelstein et al., reported both JND[2] and PSE .

The contrast in viewing conditions between Allison's and our prior studies could be determinative since there are well known differences between the apparent stability of the visual direction of small foreground objects versus that of backgrounds. For example, Matin, et al. (1982; see also Stark & Bridgeman, 1983) have shown that while the efference associated with a person's attempt to move a paralyzed eye can lead to apparent movement and displacement of a small isolated, fixated object, such illusory movement is not noted if the subjects observe a full environment instead of an isolated point. In a sense, the full environment "captures" the users' visual reference frame and thereby obscures apparent displacement otherwise associated with the efference. The illusory motion is caused in Matin's case by a mismatch between the subject's efference signal to move their eyes and the failure of them to move because of local paralysis. A similar contrast could underlie the explanation of the differences between our and Allision' et al.'s measurements of the detectability of latency since we are both asking subjects to judge the stability of a visual environment.

Accordingly, we have designed the following experiment to investigate the generality of our previous measures of user ability to discriminate latency changes. One condition replicates the environment used by Allison et al (2001). A second condition replicates the one used in our previous studies. The third combines features of the two and allows examination of whether previous determinations of latency generalize to a more complex environment exhibiting relative motion between contours during observer movement, a cue that could increase user sensitivity to latency changes. In all cases, we use a psychophysical method similar but more efficient than previous studies.

Methods

Subjects

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[1] The latency difference which is detected 50% of the time when actually present in a two alternative forced choice situation is the point of s jective equality (PSE).

[2] The change in latency required to increase or decrease detection 25% from the PSE is the just noticeable difference(JND).

Twelve subjects (9 male, 4 female, with normal or corrected normal vision; ages:21-44) naïve with respect to the experimental hypothesis participated in a repeated measures Latin square experiment. In addition, one of the authors (KM) provided an additional replication of one of the 6 cells in the Latin square design.

Apparatus and software

Custom virtual environment (VE) simulation software was executed on a with Dell Precision workstations (Dual 2.4_GHz Xeon processors, NVidia Force_4_MX-440 graphics card). The VE system employed in this work included a single receiver Polhemus Fastrak running at 120 Hz for motion sensing and a Virtual Research V8 HMD (FOV=48°). Separate software applications to interface to the Fastrak (a customized AuSIM AuTrak driver) and to model and render the experiment VE were written in Windows 2000 Visual C++ .

Participants viewed one of three VEs. The first was an empty pink environment containing only a red octahedral frame, built from back-to-back right pyramids joined at their 15 cm square base, with a combined height of 15 cm. The second was a large faceted, spherical surface (radius=100 cm) viewed from inside and texture mapped with a red and white checkerboard-like pattern, defined by 12 regular longitudinal and 5 latitudinal divisions. This environment matched the one used by Allison et al. (2001). The third environment combined the octahedron and the faceted sphere of the first two conditions. All three conditions were adjusted for approximately constant, mid-photopic space averaged luminance.

The position of the virtual octahedron was fixed in world coordinates at eye-height ~43 cm in front of the seated viewer's eye-point. At this distance, the octahedron occupied a horizontal visual angle of 20°. Custom tracker drivers and a multiprocessing, shared-memory architecture ensured a 10.4ms base latency[3] and constant 60 Hz update rate, providing the very high dynamic performance that made the following experiment possible.

Figure 1. Virtual environment display equipment

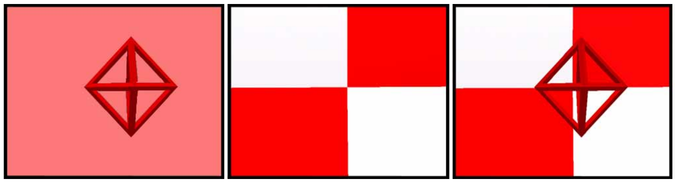

Figure 2. Screen images capturing part of the three alternative virtual environments as seen through the HMD).

Procedure and experimental design

The subjects were instructed to yaw their head smoothly and sinusoidally from side to side (30° end-to-end). They were paced by computer-generated beeps every 1 s, marking four intervals for two full back and forth motions. If they turned too far, the scene darkened by 58% to signal excessive rotation. Each visual condition remained fully visible while the stimulus motion spanned the HMD's horizontal field of view (FOV).

The judgments signaled by button pushes advanced according to an adaptive staircase algorithm (Method of Limits), incorporating descending or ascending 8.5 ms latency steps. The experiment comprised a single scripted set of 18 staircases, 6 staircases per visual condition, 3 ascending and 3 descending with each set of two staircases being interleaved to prevent subjects' prediction. There were three sets of interleaved staircases per visual condition). The reference latency condition (R) was fixed at 10.4 ms. and compared with a second probe (P) condition that could be varied. The experimental conditions were presented to all subjects in counterbalanced order using a Latin square design, with a pair of subjects being assigned to each of the 6 possible sequences of the three viewing environments.

Results

Psychometric functions were determined for each viewing condition for each subject by a least-squares fitting procedure that estimated the point of subjective equality (PSE), and the just noticeable difference (JND). The former reflects individual subjects' biases in determining the perceptual equivalence of differing physical latencies; the latter reflects subjects'

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[3] The latency between the transduction of a mechanical event by the Fastrak end-to-end VE system latency was verified for all environments (Hill, Adelstein, & Ellis, submitted to IMAGE Society 2004 meeting) using techniques previously described (Adelstein, Johnston, & Ellis, 1996).

sensitivity to latency changes. As can be seen in Figure 3 and Table 1, the fits of the psychometric functions were reasonably good. The overwhelming majority of fits for most subjects were highly statistically significant, with the poorer fits being distributed roughly evenly across the experimental conditions.

The two estimated parameters, subjected to a two-way parametric ANOVA of sequence and environmental condition, showed no statistically significant main effects or interaction (JND: Viewing condition: $F_{2,14}$=0.36,ns; Sequence: $F_{5,7}$ =0.69, ns.; ConditionXSequence: $F_{10,14}$=0.61,ns. PSE: Viewing condition: $F_{2,14}$=0.47,ns; Sequence: $F_{5,7}$=0.1.68,ns.; ConditionX-Sequence: $F_{10,14}$=0.97,ns.). The lack of a main effect of condition was also confirmed by a Friedman ANOVA (JND: X^2_2=4.2, ns;. PSE: X^2_2=2.0, ns.).

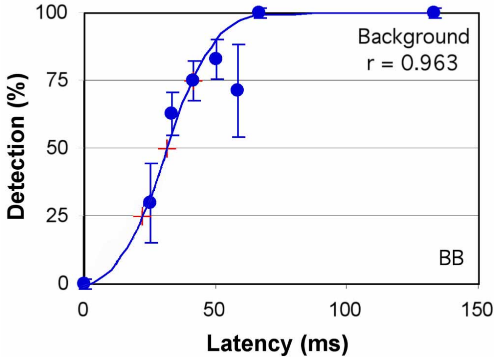

Figure 3. Psychometric function for latency sensitivity of a representative subject.

Subject	Correlation with best fitting Ogive		
	Object	*Background*	*Both*
AG	0.993	0.955	0.933
BB	0.992	0.964	0.670
BM	0.878	0.933	0.947
CM	0.981	0.992	0.998
EF	0.965	0.984	0.843
JA	0.698	0.742	0.935
KM	0.988	0.990	0.714
LL	0.871	0.932	0.980
MS	0.969	0.788	0.961
ME	0.529	0.937	0.280
PH	0.992	0.919	0.987
SF	0.997	0.990	0.994
TL	0.987	0.985	0.991

Table 1. Correlations between the standard cumulative gaussian gaussian model for a psychometric function and subjects data for each visual condition. ($p < 0.01$, $p < 0.05$, ns.)

Additionally, there was no effect of order as determined by an independent one-way ANOVA (JND: $F_{2,24}$=1.757,ns.; PSE: $F_{2,24}$=0.05,ns.). All subjects' individual parameter estimates and group medians and interquartile range (IQR) corresponding to these analyses are presented in Figures 4 and 5. Note that were the precision of the estimates (corresponding standard errors of means) for each condition to be plotted, they would in general be hard to see on a scale large enough to present all of the individual data.

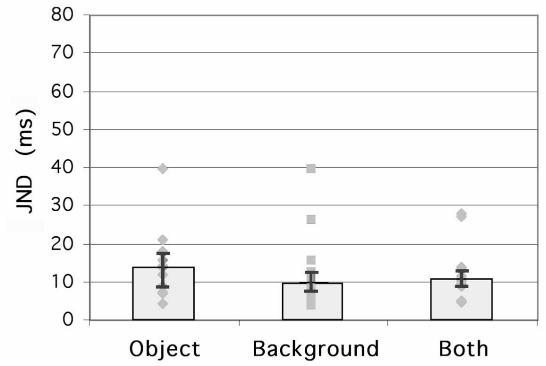

Figure 4. Medians, interquartile range and individual data points.

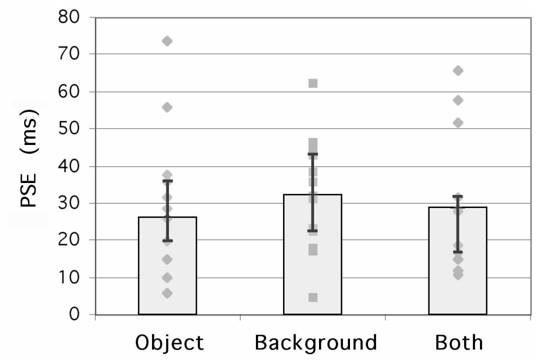

Figure 5. Medians, interquartile range and individual data points

Figure 5.

Discussion

Our results present a precise and striking contrast with those of Allison et al., (2001), especially for the *Background* condition that is the replication of their experiment. Our much more detailed results show that subject's sensitivity and bias to latency change to be quite acute. In particular, our measured bias reflected in the PSE is much lower than Allison et al.'s reports of 200 ms and higher. Furthermore, our results are consistent with our previous studies and those of Regan et al. (1999) whose experiments were conducted using somewhat different psychophysical techniques and very different viewing techniques, and visual environments. We believe that one explanation for our subjects being more sensitive is that we made sure they understood what latency "looked like" in the display before we began the experiment. We have found though unpracticed subjects require careful discussion to understand exactly what latency means visually, once they understand it, they are sensitive observers. We see this in the precision of our population parameter estimates and by the absence of sequence or order effects.

We also can see that increasing the complexity of the environment with the combination of a foreground with a background did not increase the subjects' sensitivity to detecting a latency change. This equality suggests that the shear evident in the *Both* condition does not necessarily aid latency discrimination. Some insight into why the added complexity in the image combining a foreground and a background may be found in comments solicited from subjects regarding how they made their discriminations. Several subjects remarked in subsequent studies that they focused on one feature in the display such as a particular corner or edge and then judged its stability during their head movements. Clearly, such a strategy could bypass potential effects due to the presentation of a shear.

It should be noted additionally that the head movement studied in this experiment might not have been optimized for latency detection. During initial experimentation, one subject (SF) not following instructions had to be reminded not to use a jerky head movement. Analysis of these data, which were later discarded, showed a dramatically better JND. Finally it should be noted that, our study of the role of increased spatial complexity could be pursued more vigorously with a more complex, photorealistic environment with many objects and depth planes. Such as study has been completed and will be reported elsewhere (Mania, Adelstein, Ellis, & Hill, 2004). It confirms that increased scene complexity does not affect latency sensitivity for the kind of discrimination with focussed attention that we have been testing.

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