Taking Fitts Slow:

The Effects of Delayed Visual Feedback on Human Motor Performance and User Experience

by

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ABSTRACT

The present studies investigated the separate effects of two types of visual feedback delay – increased latency and decreased updating rate – on performance – both actual (e.g. response time) and subjective (i.e. rating of perceived input device performance) – in 2-dimensional pointing tasks using a mouse as an input device. The first sub-study examined the effects of increased latency on performance using two separate experiments. In the first experiment the effects of constant latency on performance were tested, wherein participants completed blocks of trials with a constant level of latency. Additionally, after each block, participants rated their subjective experience of the input device performance at each level of latency. The second experiment examined the effects of variable latency on performance, where latency was randomized within blocks of trials.

The second sub-study investigated the effects of decreased updating rates on performance in the same manner as the first study, wherein experiment one tested the effect of constant updating rate on performance as well as subjective rating, and experiment two tested the effect of variable updating rate on performance. The findings suggest that latency is negative correlated with actual performance as well as subjective ratings of performance, and updating rate is positively correlated with actual performance as well as subjective ratings of performance.

ACKNOWLEDGMENTS

No amount of gratitude stated on this page can significantly express my thanks to each of my committee members: Dr. Wu, for inspiring ideas and pushing me to reach my potential; Dr. Branaghan, for deepening my interest in cognitive psychology; and Dr. Hout for inspiring my interest in cognitive psychology to begin with. For these and many other reasons, I am forever grateful.

DEDICATION

To my wife, Brittany, for pushing me to follow the path I thought right, for being there every step along the way, and for putting up with me in general. And to my dogs, for keeping me sane.

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In the current age, more and more complex motor tasks are being carried out on computers. For instance, surgeons can carry out complex procedures remotely using video feeds and robotic surgical systems, doing the same work, but with greater level of precision and a broader reach of access (Marescaux, et. al., 2001; Kim, et. al., 2005; Sterbis, et. al., 2008). No longer does one have to be in the same place as their opponent to play a game of basketball, nor do they even have to be athletic; they just have to jump on a computer connected to the internet and can play anyone, anywhere in the world. In fact, entire environments are now being virtually simulated to accomplish a multitude of things from training to gaming. For example, advances in virtual reality applications allow medical students to hone their surgical skills in a simulated environment without the risks involved in practicing on real patients (Grantcharov, et. al., 2004). Further, devices like the Oculus Rift allow users to fully immerse themselves in the environments of the games they are playing.

These advancements provide broader access and an endless amount of possibilities to make complex motor tasks more efficient, more precise, and more engaging. With that said, carrying out complex motor tasks on computers does not come without limitations. Unlike carrying out complex motor movements in the real world, certain types of sensory feedback are often delayed – or even unavailable – when performing complex motor tasks on a computer. Limitations of sensory feedback used to guide such complex motor tasks can reduce user performance and subjective experience. One such limitation – and the focus of the current work – is visual feedback delay.

Imagine sitting in front of your PC, playing Madden 16 (a popular simulated football videogame) online, against a friend on the other side of the country. You receive the opening kickoff and try to run it back, attempting to evade your opponent's defenders, but the movement on your screen – your visual feedback – is clearly lagging behind your controls and your run is stopped almost immediately. Later in the game you realize that you seem to be missing your target receiver on almost every passing play because the images on your screen are refreshing at a delayed rate. Not only is your performance faltering, but with the delay, the game feels less playable and very frustrating.

These are examples of visual feedback delays – via input latency and low frame-rate, respectively – that can hinder both user performance and overall user experience in complex, visually-mediated motor tasks carried out on computers.

Visual feedback delays

Visual feedback delays have been shown to have a negative effect on various measures of performance on a variety complex motor movements. An early study of the effect of visual feedback delays on performance, conducted by Smith and Bowen, utilized a discrete 1-dimensional movement task to assess the effects of delay, displacement, and movement time on performance. Using a complex system consisting of a video camera, video recorder, video delay unit, a mirror, and a pair of monitors, the investigators were able to impose both visual displacement and visual feedback delay during the experimental trials. Participants were instructed to point a stylus to a target over a specified time. Feedback was provided to participants after each trial regarding their movement times to consciously speed up or slow down movement time for the next trial.

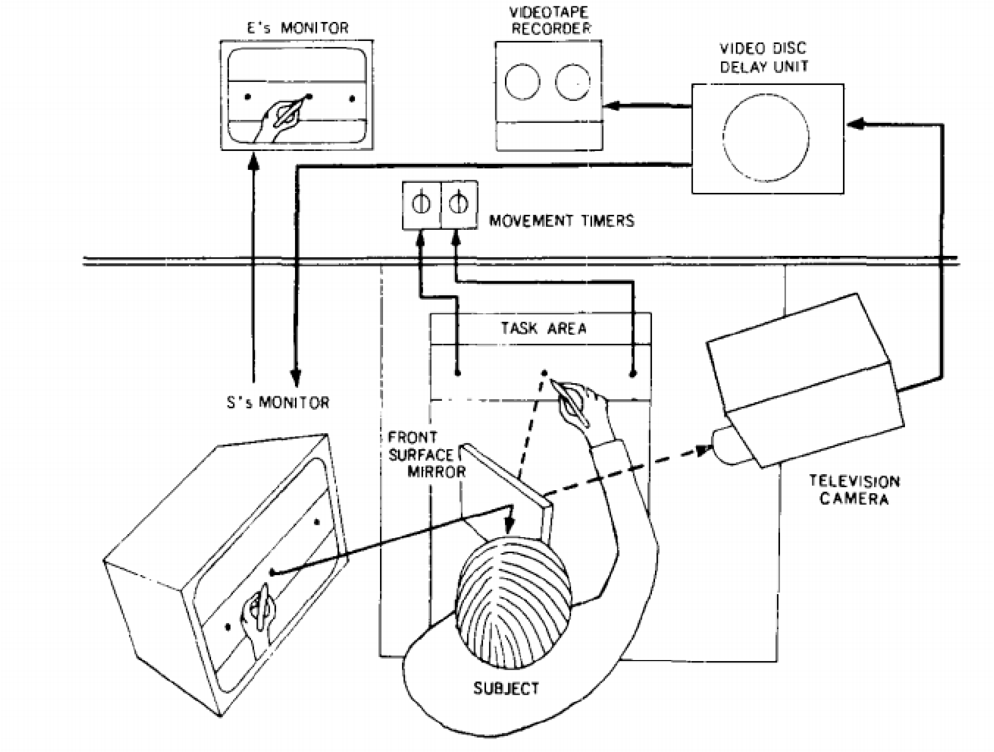

Figure 1: Experimental setup in Smith and Bowen's 1980 study.

Results showed that delayed visual feedback – as well as image displacement – had a significant effect on pointing accuracy (Smith & Bowen, 1980). Further studies building upon the findings of Smith and Bowen within 1-dimensional movement tasks showed that delayed visual feedback has a negative impact on performance in both discrete pointing tasks – using a mouse as an input device – and serial tapping tasks (MacKenzie & Ware, 1993; So & Chung, 2005).

Bryson (1993) investigated the effects of both lag and frame rate on 2-dimensional target tracking by having participants follow a target square, moving along a random path, with their cursor, as closely as possible. The target 5x5 pixel target square ran along a path composed of 10 sinusoids, or individual sine wave curves. Each phase of the sinusoid was randomized to ensure that the path was unpredictable (i.e. not starting each sinusoid from the same horizontal coordinate) and the frequency of each sinusoid was inversely related to its amplitude. Results showed that performance on the tracking task was degraded when delayed was imposed as well as when frame rates were reduced (Bryson, 1993). Other studies also reported similar findings (Miall, Weir, & Stein, 1985; Foulkes & Miall, 2000; Miall & Jackson, 2006).

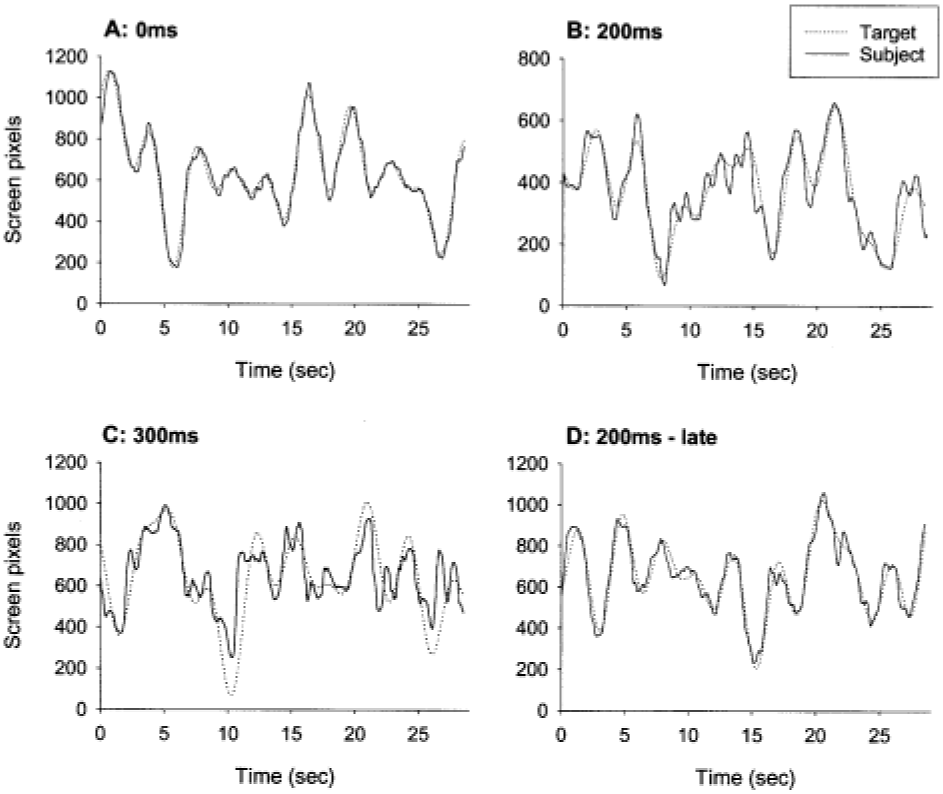

Figure 2: Illustration of target path and subject path in a target tracking task without delay from 0ms to 300ms (Foulkes & Miall, 2000).

A second experiment within Bryson's 1993 study evaluated the effects of lag and reduced frame rate on a (2-dimensional) placement task. Participants were to start with their cursor inside of a 10x10 pixel square at the lower left hand corner of a display, after a short delay a 20x20 pixel, hollow centered target square would appear at a random location on the screen. To complete a trial, participants would navigate to the target square as quickly as possible and stay within the target square's hollow center for two full seconds. The results of this experiment showcased a decrease in performance – the time taken to navigate to the target square – when both delay was imposed as well as when frame rates were reduced. There also appeared to be an interaction effect between target ID and delay, and target ID and frame rate, wherein the addition of both visual feedback delays increased movement time more greatly than ID alone.

To further assess the intricacies of delayed feedback on placing tasks, a recent study by Fujisaki (2012) sought to investigate the two main mechanisms that contribute to performance in visually guided motor movement: temporal and spatial feedback. The study started with an experiment in which 24 participants were tasked with placing as many pegs into a grooved pegboard within one minute with visual feedback being delayed – delays of 120ms to 2,120ms were imposed in 16 steps. Participants were also given time to practice prior to the actual experiment in order to be acclimated to the delay inherent in the system. Results showed that performance (i.e. the number of pegs placed within one minute) decreased with increasing delay. Specifically, there was a sharp drop in performance up to 490ms and a more gradual decrease in performance thereafter. Fujisaki carried out three additional experiments – with 13 of the initial 24 participants – to further test the effects of delayed visual feedback with available haptic feedback to assist in guiding peg placement. The experiments suggested that spatial information via haptic feedback did increase peg placement performance, but the visual feedback delays still kept performance at a lower level than without. The same effects of visual feedback delay on placement and tracking tasks have been further corroborated by studies examining complex motor tasks in virtual reality applications (Ware & Balakrishnan, 1994; Watson, et. al., 1997).

Figure 3: Experimental apparatus from Fujisaki's 2012 investigation.

Foulkes and Miall (2000) investigated the ability for humans to adapt to constant delayed visual feedback in target tracking tasks. In their study, participants were instructed to track a target, on a display, with a cursor that was controlled by a joystick. The target followed what the experimenters called a "pseudo-random" path that was essentially a randomization of independently combined, "non-harmonic" (non-overlapping) sinusoids, with pre-determined frequencies, for both the x and y axes. On each trial, participants were instructed to follow the target along this "pseudo-random" path as closely as possible. The target followed what the experimenters called a "pseudo-random" path that was essentially a randomization of independently combined, "non-harmonic" (non-overlapping) sinusoids, with pre-determined frequencies, for both the x and y axes. During each trial, participants would follow the target along this "pseudo-random" path as closely as possible. Three groups of participants were tested: Group 1 completed 40 test trials with no delay, Group 2 completed 40 test trials with 200ms delay, and Group 3 completed 40 test trials with 300ms of delay. There were "perturbed" trials every five trials, in which the target's path would deviate by instantaneously increasing in amplitude in order to assess the participants' responsiveness to large changes in the target path during tracking. The results showed that participants, while seeing an initial decrement in performance, began to adapt to the visual feedback delay and their performance increased significantly. Furthermore, the participants in Groups 2 & 3 who completed trials with delayed visual feedback initially greatly overshot the target on perturbed trials, but adapt to the delayed feedback to the extent that the overshot the target much less on perturbed trials later in the experiment. These results have since been replicated showing that the human visuomotor system can adapt to constant delays much like it can do other exogenous and endogenous disturbances (Foulkes & Miall, 2000; Miall & Jackson, 2006).

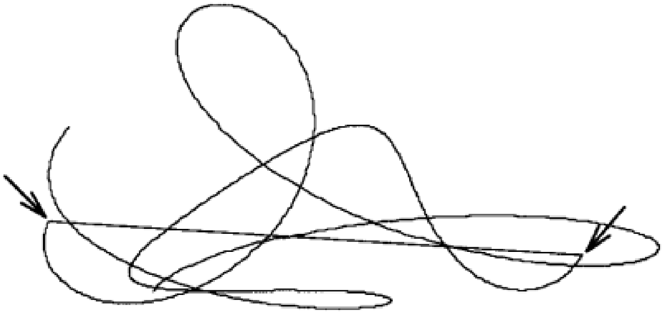

Figure 4: An example of a "pseudo-random" target path (Foulkes & Miall, 2000).

Beyond the effect that visual feedback delay has on performance, it has also been shown to impact user experience in a variety of ways. For instance, it has been found that "watchability" of video is diminished with decreasing frame rates, especially in the case of high-action video – such as in live-streaming sports games, online first-person shooters, or even a run-of-the-mill racing game – although the effects on experience are less pronounced in low-action video (Apteker, et. al., 1995). Similarly, it has been found that user perception of video quality in first-person shooters is diminished when presented video at lower frame rates and lower-quality resolutions suggesting that – although it has been shown that performance is better when higher frame rates are given priority over better resolution – user experience is tied to both performance and the visual appeal of the video itself (Claypool, Claypool, & Damaa, 2006). Visual feedback delay can have such a profound effect on subjective experience that when, in immersive virtual environments, users often experience "simulator sickness", which is generally thought to be an effect of relatively long input latencies (Steinicke & Bruder, 2014). With this in mind, how can subjective user experience, in the presence of visual feedback delays, be modeled and predicted? What variables can be used for such a model? Finally, performance on what type of task will best inform such a model?

Fitts' Law and motor control

Proper motor control is critical when carrying out precise procedures such as telesurgery and videogame play. Several factors come into play when informing motor control, most notably, visual feedback. The ability to see how one is moving, the distance to and size of what one is moving towards, etc. are all essential pieces of information, collected and processed through our visual pathways, which help to guide motor control. In fact, motor control is so heavily reliant on visual information regarding the physical nature – the size of and distance to – of what one is moving towards that a fundamental law of motor control, Fitts' Law, is able to reliably predict movement speed and accuracy of movement based on that information (Fitts, 1954).

Fitts' Law has long been the standard for predicting movement time and accuracy – or the capacity of the human motor system – in targeted pointing tasks. In 1954, Paul Fitts' set out to examine the maximum capacity of the human motor system, predicting that the capacity, and therefore the performance of the system, could be predicted in a similar way that the maximum rate of information transfer over a communication channel could be predicted by Shannon's Channel Capacity Theorem. Fitts' supposition was that by using variables analogous to those used in Shannon's Channel Capacity Theorem – which states that the maximum rate of information transfer over a communication channel can be predicted, essentially based on the bandwidth of the channel as well as the amount of noise present – within a 1-dimensional, targeted pointing task, one could accurately estimate the maximum capacity of the human motor system (Shannon & Weaver, 1949). Fitts hypothesized that target width and target amplitude (distance to the target) could be used to predict the maximum capacity of the human motor system. As an aside, from those two variables, Fitts established a combined estimate of the inherent difficulty – commonly referred to as the index of difficulty (ID) – of the motor task, which was hypothesized to be negatively correlated with performance (Fitts, 1954; MacKenzie, 1992). In order to test the efficacy of his hypotheses, Fitts had participants carry out a 1-dimensional, targeted pointing – or "tapping" – task in which participants rapidly pointed to – or "tapped" – two rectangular targets repeatedly, using a one-ounce or one-pound stylus. During each block of trials, the width of the rectangular targets was held constant, as was the targets' amplitude (distance between the two targets). As hypothesized, there was a negative correlation between ID and overall performance, wherein the greater the distance between the two targets, and the narrower the width of the targets, the worse the performance (Fitts, 1954).

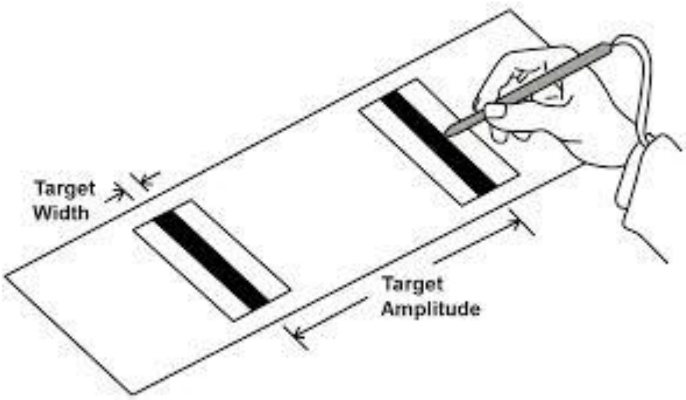

Figure 5 A representation of Fitts' tapping apparatus

From those findings Fitts' Law was born. Simply stated, Fitts' Law is able to estimate movement time (MT) based the index of difficulty (ID) of the pointing task, where ID = $\log_2*(2A/W+1)$ (A being target amplitude and W being target width). The full equation [$MT=a+b*\log_2(2A/W+1)$] also includes two empirically derived constants: a – the intercept – and b – the regression coefficient.

Discrete movements. Since its inception, Fitts' Law has been validated in many experimental contexts. For instance, although the law was initially meant to explain only a very specific type of serial "tapping" task, Fitts himself was able to validate his law in discrete tapping tasks ten years later (Fitts & Peterson, 1964). Much like the tapping task in Fitts' 1954 study, participants were tasked with tapping two rectangular targets situated across from each other, but rather than repeatedly tapping the targets back-and-forth, participants started the trial with their stylus at rest on a fixation point in between the two targets and their gaze focused on a fixation cross between two "stimulus" lights. The participants were then prompted to move to either the left or right target corresponding with which "stimulus" light was illuminated (left or right). The results of this experiment indicated that, like in serial tapping movements, performance in discrete, 1-dimensional, targeted pointing movements was modulated by the intended targets' ID (Fitts & Peterson, 1964). This study still had its limitations in that the law was once again tested only using 1-dimensional movement.

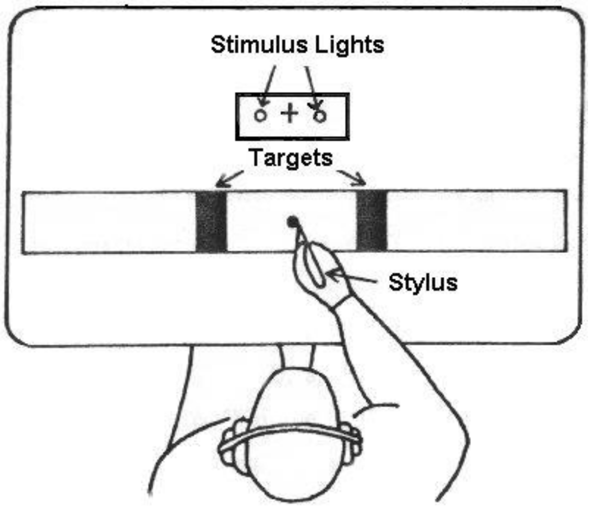

Figure 6: The layout used to test Fitts' Law on discrete motor movements.

2-dimensional movement. Jagacinski and Monk (1985) tested whether Fitts' Law could be extended to more complex, 2-dimensional movements. Participants used either a joystick or a head-mounted sight – on which they received training prior to the experimental trials – to navigate to circular targets – although it has been demonstrated that target shape is largely irrelevant (MacKenzie & Buxton, 1992) – on a screen in one of 72 positions: eight radii (or directions), three target amplitudes, and three target widths. Participants would first work through a fixation process at the beginning of each trial and, when completed, would be rapidly presented with a target, which they were to navigate to as quickly as possible using whichever input device they were using. Results indicated that Fitts' Law – or rather ID – was "a good linear predictor of movement time", much how it was in 1-dimensional pointing tasks (Jagacinski & Monk, 1985). Further studies investigating the efficacy of Fitts' Law in predicting performance in 2-dimensional movement tasks corroborated this evidence (MacKenzie & Buxton, 1992; Mottet, et. al., 1993). In addition to the joystick, head-mounted sight, and stylus, many other input devices have been examined to assess the impact of their use on Fitts' Law. All pointing devices have been found to exhibit similar adherence therein (Jagacinski & Monk, 1985; MacKenzie, Sellen, & Buxton, 1991; Teather, Pavlovych, Stuerzlinger, & MacKenzie, 2009).

Hypotheses

The purpose of this study was to examine the effects of delayed visual feedback on both motor performance and users' subjective experience. More specifically, four experiment were conducted to answer the following research questions:

R1: How would a user's performance in 2-dimensional pointing tasks be influenced by the latency of visual feedback? Could people adapt to a constant latency, and how would their performance differ in the situations of constant vs. unpredictable visual latency?

R2: How would people perform in 2-dimensional pointing tasks under different updating rates of visual feedback? Could people get adapted to a reduced updating rate of visual feedback?

R3: How would users' subjective perception of device usability change with the latency and/or updating rate of visual feedback, and how well could users' subjective experience be predicted from their motor performance?

With regard to the research questions related to the effects of visual latency, we hypothesized that changes in latency would be negatively correlated with task performance (greater latency resulted in decrease in performance), participants would perform better when latency was constant across trials than as compared to the condition where latency varied across trials, and participant's subjective perception of device usability would be negatively correlated with changes in latency (greater latency would result in decreased subjective rating of input device usability).

Similarly, the hypotheses about the research questions related to FPS were that updating rate would be positively correlated with task performance (lower updating rate would result in decreased performance), participants would perform better when updating rate was constant than when latency was variable, and participant's perception of device usability would be negatively correlated with changes in updating rate (lower updating rate would result in lower ratings of device usability).

It was also the intent of this study to establish a predictive model of user experience that would take into consideration the factors of delay examined – both latency and updating rate – as well as participants' task performance and subjective ratings.

Sub-study 1

This sub-study contained two experiments, which were designed to address R1 and investigate the influence of constant or variable visual latency on user's performance of 2-dimensional pointing tasks and also their perception of device usability.

Method.

Participants. Ten undergraduate students at the Arizona State University Polytechnic Campus were recruited using Arizona State University's SONA Research Participation System. Participants were awarded credit towards their introductory psychology course requirements as compensation for participating in the study. All participants had normal or corrected to normal vision.

Materials. During the study, participants were positioned in an adjustable computer chair in front of a desk with a height of approximately three feet. Participants used a mouse to point to and click fixation boxes and target circles on a 27" Acer display (resolution: 1920x1080@120 Hz), with a maximum viewing angle of 160 degrees. The experiment was run using a Dell workstation.

Stimuli. Four target amplitudes of 80px, 220px, 360px, and 500px were coupled with a circular target with a constant radius of 16px to establish a set of target IDs on which to grade performance. Additional dummy stimuli were inserted at random between true stimuli in order to increase perceived variation in stimuli. All stimuli were presented in random order within blocks. All stimuli were white and displayed on a black background.

Design. The independent variable in this experiment was the latency in visual feedback, which had five levels ranged from 0 to 16 frames with a step of 4 frames (i.e., 0-133ms with a step of 33ms). The experimental trials were blocked by different latency levels: Participants went through five pairs of blocks with each pair having a constant level of latency for all trials in each block. Each block contained a total of 40 trials, 28 of which were experimental trials (i.e., seven repetitions of the four stimuli of different IDs) and another 12 of which were "dummy" trials with random levels of ID. The test order these experimental blocks were counterbalanced across participants using a Latin square design.

The dependent variables were response time and accuracy, which were used to assess the participant's performance at each level of latency. In addition, after having completed all trials at one latency level, participants were asked to complete a five-question questionnaire to report their subjective experience about the usability of the mouse at the latency level tested. Ratings were collected via three five-point Likert scales and two nine-point Likert scales (questionnaire in appendix).

Procedure. At the beginning of each trial, the participant is presented with a fixation box in the center of the screen. The participants were instructed to click the fixation box in order to start the trial. Once the fixation box was clicked a target circle appeared at a random point on the screen. The participant was instructed to move as quickly and as accurately as possible to the target circle and click inside of it. Once the participant clicked inside of the target circle it would disappear and the fixation box would appear in the center of the screen again signaling the beginning of the next trial.

Participants first were run through two "demo" blocks to familiarize them with the experimental procedure. Practice trials had the same procedure as the experimental trials with the exception that the sizes and IDs of targets were different from the experimental stimuli. The first "demo" block was completed by the participant without any latency imposed on the cursor, whereas the second "demo" block – started after one minute of rest – was completed with a 200ms delay imposed on the cursor across trials, in order to acclimate the participant to the experimental procedure.

Results.

Response time. Response time data were analyzed using a 4x5 repeated measures ANOVA revealing significant main effects of both ID [$F(3, 27) = 113.008$, $p<.001$, $\eta_p^2 = .926$] – response times increased with increased ID – and Latency [$F(4, 36) = 29.494$, $p<.001$, $\eta_p^2 = .766$] – response times increased with increased delay. Additionally, there was an interaction effect of ID* Latency [$F(12, 108) = 42.789$, $p<.001$, $\eta_p^2 = .826$]. As shown in Figure 7, response time increased almost linearly with ID at all latency levels but with a greater rate for longer latency.

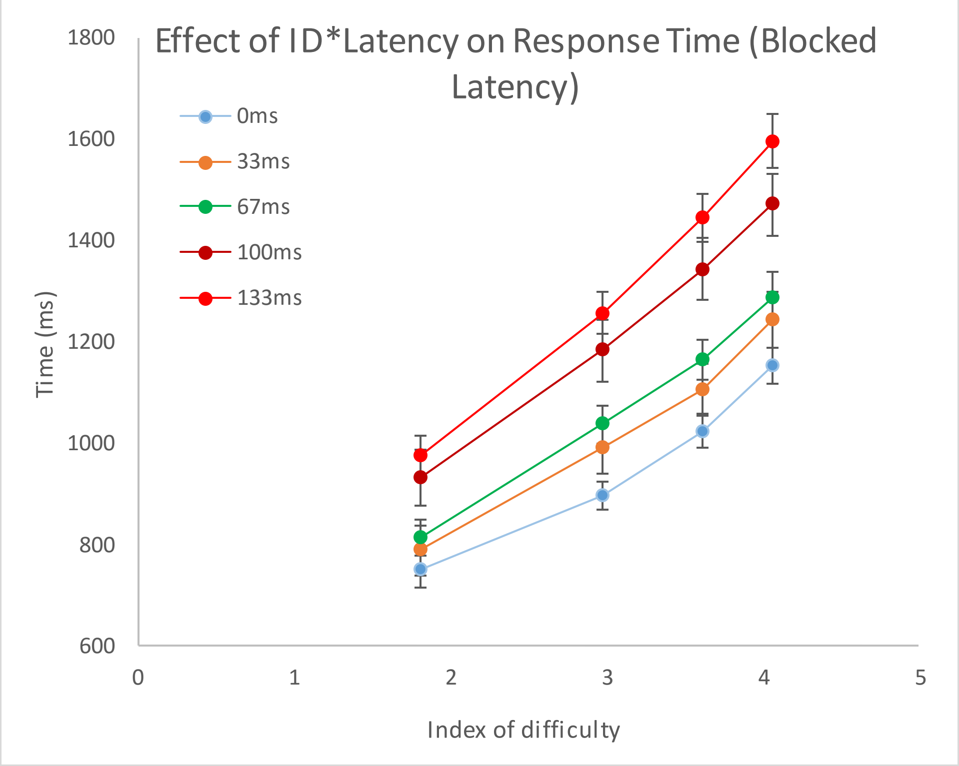

*Figure 7: Effect of ID*latency on response time (blocked latency)*

Subjective opinion. A simple regression analysis was used to analyze the relationship between subjective ratings and level of latency. It was found that subjective rating had a significant negative correlation with latency [$b = -.13$, $t(3) = -11.288$, $p < .01$] and that latency predicted a significant proportion of variation in subjective ratings [$R^2 = .97$, $F(1) = 127.41$, $p < .01$], suggesting that accurate predictions of user experience may be made by looking at latency (*see Figure 8*).

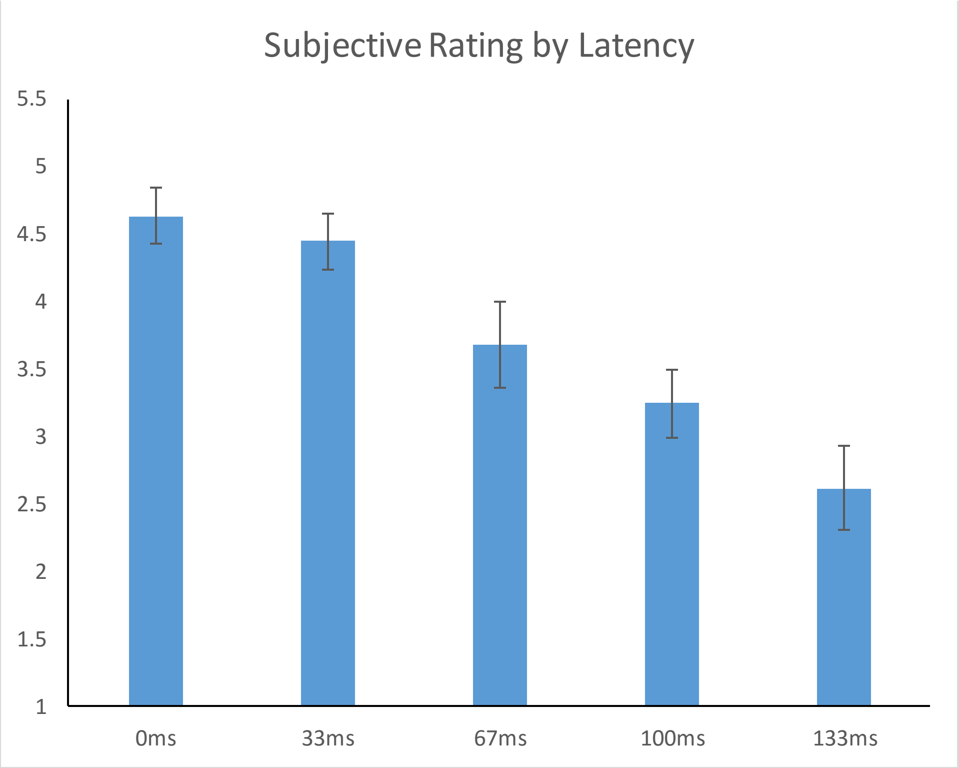

Figure 8: Subjective rating by latency level

Experiment 1B

Method.

Participants. Another group of ten undergraduate students participated this experiments with consent. All participants had normal or corrected to normal vision.

Materials & Stimuli. The experimental setup and stimuli were identical to Experiment 1a.

Design. The same independent and dependent variables were used in this experiment. The experimental design was identical to Experiment 1a, with the only exception that the experimental trials of difference latency levels were presented in a random order within each block, rather than being grouped by different levels of latency. A total of 7 blocks were tested, each of which contained a total of 55 trials, 40 experimental trials and 15 "dummy" trials.

Procedure. The experimental procedure was same as described in Experiment 1a.

Results.

Response time. Data were analyzed using a 4x5 repeated measures ANOVA revealing significant main effects of both ID [$F(3, 27) = 280.064$, $p<.001$, $\eta_p^2 = .969$] – response times increased with increased ID – and Latency [$F(4, 36) = 20.544$, $p<.001$, $\eta_p^2 = .695$] – response times increased with increased delay. Additionally, there was an interaction effect of ID* Latency [$F(12, 108) = 80.647$, $p<.001$, $\eta_p^2 = .900$] (see *Figure 9*) indicating that response time increased over the IDs at a greater rate for longer latency.

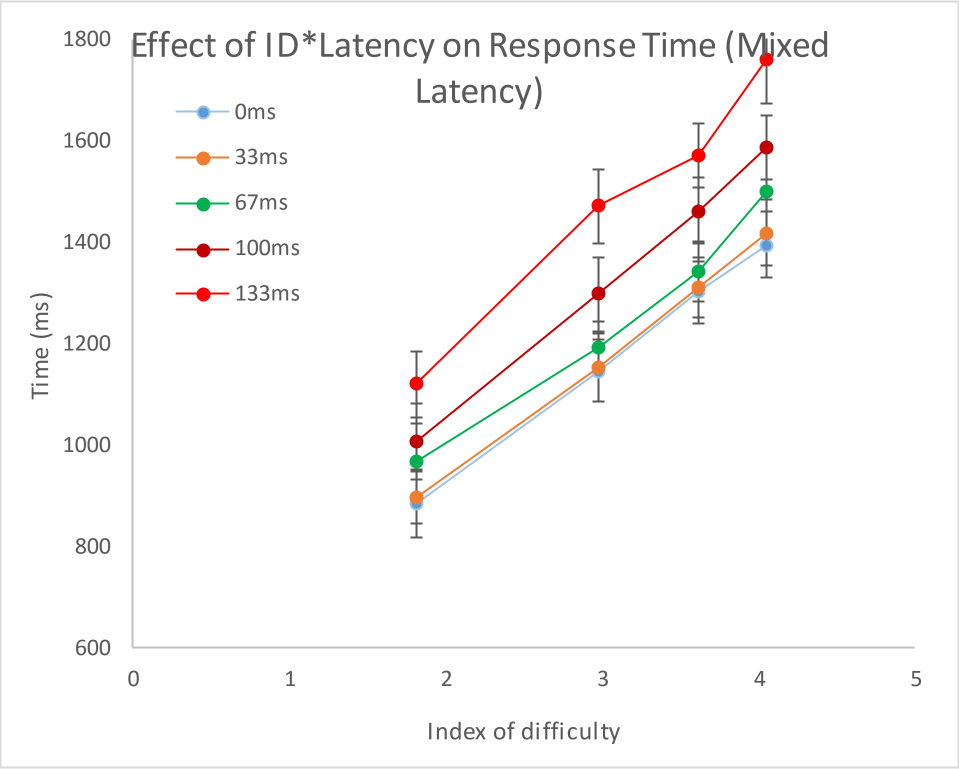

*Figure 9: Effect of ID*latency on response time (mixed latency)*

An additional 2x4x5 mixed-measures ANOVA was used to compare Experiment 1a and 1b and assess if the participants could adapt to a constant latency. A significant effect of blocked vs. mixed latency was found [$F(1, 18) = 5.189$, $p<.05$, $\eta_p^2 = .224$].

Study 1 discussion

As evidenced by both experiments in study 1, latency, ID, and consistency in level of delay had clear effects on response time, signifying that visual feedback delays imposed via latency have similar effects in 2-dimensional pointing tasks as they do in 1-dimensional tasks. Additionally, a significant difference in performance (response time) between experiments 1A (blocked latency) and 1B (mixed latency) was found wherein performance was better overall in experiment 1A suggesting – as previous research has suggested – that an adaptation effect might exist. Finally, a clear relationship between latency level and subjective experience of input device performance was found, wherein longer latency levels negatively impact subjective experience.

Sub-study 2

In this sub-study, two experiments were conducted using the same design as sub-study 1 to investigate the effects of reduced updating rate in visual feedback on user's performance of the pointing task and their perception of device usability.

Experiment 2A

Method.

Participants. Ten new participants were tested in this experiment with consent. All had normal or corrected to normal vision. None of them participated in Sub-Study 1.

Materials & Stimuli. The experimental setup and stimuli were identical to Experiment 1a.

Design. The experimental design was parallel to Experiment 1a, with the only exception that the independent variable was the updating rate of visual feedback instead of latency. Five levels of updating rate were tested with counterbalanced order using a Latin square design: 10Hz, 15Hz, 20Hz, 24Hz, or 30Hz. The dependent variables was same as in Experiment 1a.

Procedure. The experimental procedure was same as described in Experiment 1a. Two blocks of practice trials were given to participants to familiarize them with the experimental procedure. The practice trials used the same procedure as the experimental trials with the exception that the sizes and IDs of targets were different from the experimental stimuli. The first block was run at a fast updating rate of 120 Hz and the second at a slow updating rate of 8Hz.

Results.

Response time. As in Experiment 1a, data were analyzed using a 4x5 repeated measures ANOVA. The results found significant main effects of both ID [$F(3, 27) = 87.892$, $p<.001$, $\eta_p^2 = .907$] – response times increased with increased ID – and Updating-rate (UR) [$F(4, 36) = 8.534$, $p<.001$, $\eta_p^2 = .487$] – response times increased with decreased updating rate. There was an interaction effect of ID*UR [$F(12, 108) = 89.876$, $p<.001$, $\eta_p^2 = .909$] (see *Figure 10*) indicating that response time increased at a greater rate for lower updating rates.

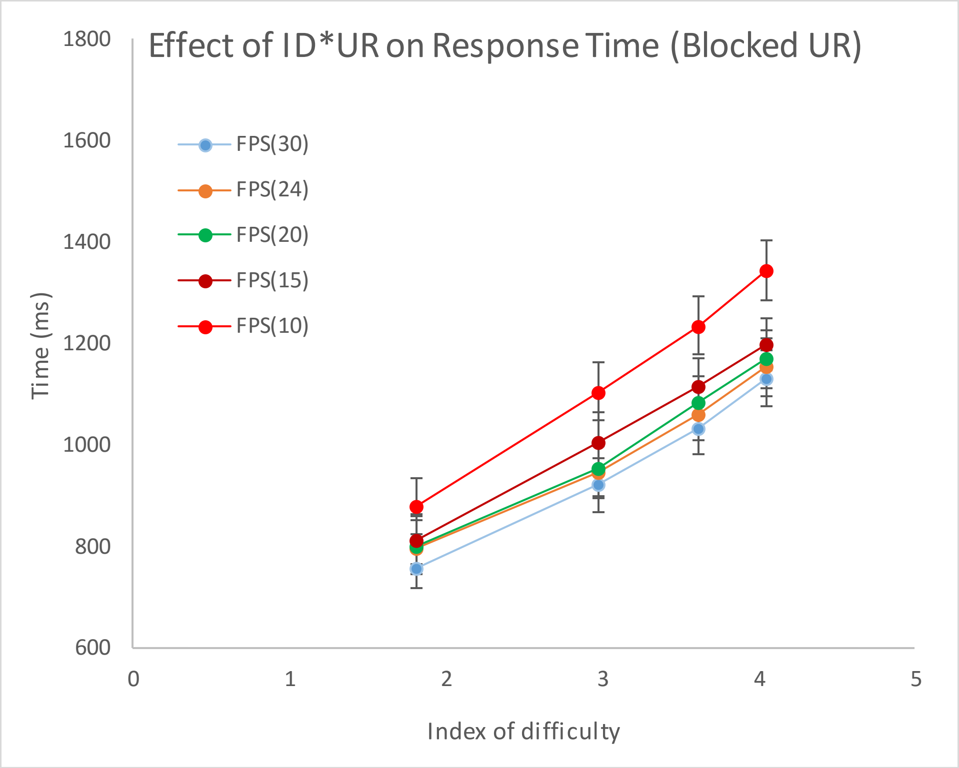

*Figure 10: Effect of ID*UR on response time (blocked UR)*

Subjective opinion. A simple regression analysis was used to analyze the relationship between subjective ratings and level of UR. It was found that subjective rating had a significant negative correlation with UR [$b = 0.085$, $t(3) = 5.621$, $p < .05$]

and that UR predicted a significant proportion of variation in subjective ratings [R^2 = .91, $F(1) = 31.603$, $p < .05$], suggesting that accurate predictions of user experience may be made by looking at UR (*see Figure 11*).

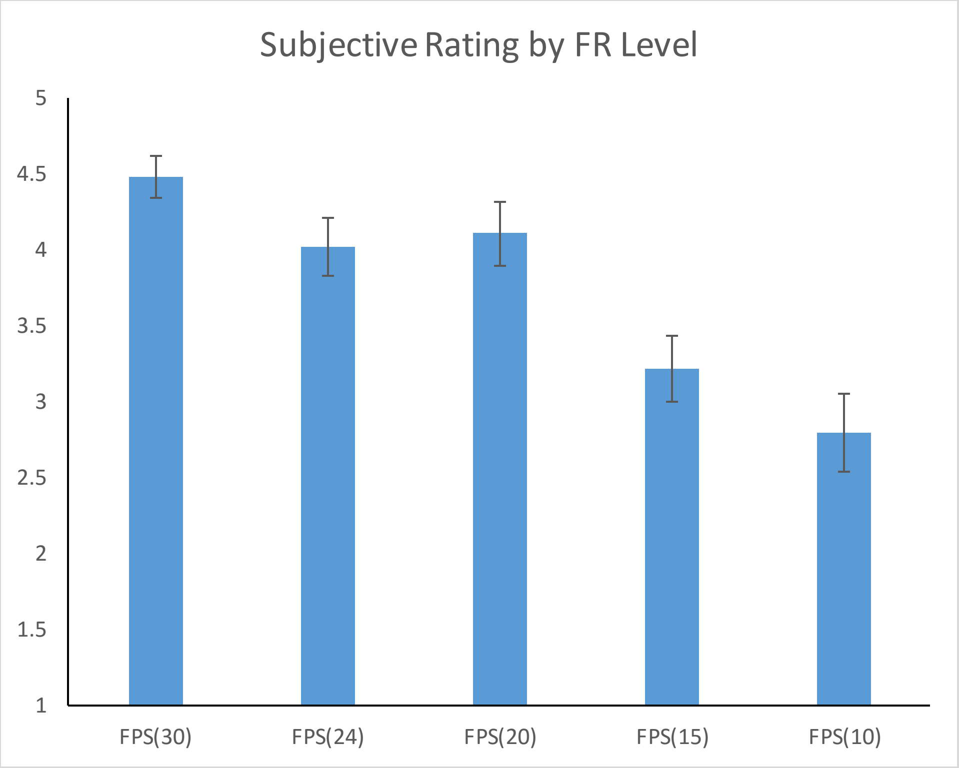

Figure 11: Subjective rating by UR level

Experiment 2B

Method.

Participants. Ten new participants were tested. All had normal or corrected to normal vision.

Materials & Stimuli. The experimental setup and stimuli were identical to Experiment 2a.

Design. The same independent and dependent variables were used in this experiment, and the design was identical to Experiment 2a, with the only exception that the experimental trials of different updating rates (URs) were presented in a random order within each block, rather than being grouped by different URs. A total of 7 blocks were tested, each of which contained a total of 55 trials, 40 experimental trials and 15 “dummy” trials.

Procedure. The experimental procedure was same as described in Experiment 2a.

Results.

Response time. Data were analyzed in the same as in Experiment 2a. A 4x5 repeated measures ANOVA revealed significant main effects of both ID [F(3, 27) = 115.766, p<.001, η_p^2 = .928] – response times increased with increased ID – and UR [F(4, 36) = 6.840, p<.001, η_p^2 = .432] – response times increased with decreased updating rate. A significant interaction effect of ID*UR was also found [F(12, 108) = 88.341, <.05, η_p^2 = .908] (see *Figure 12*).

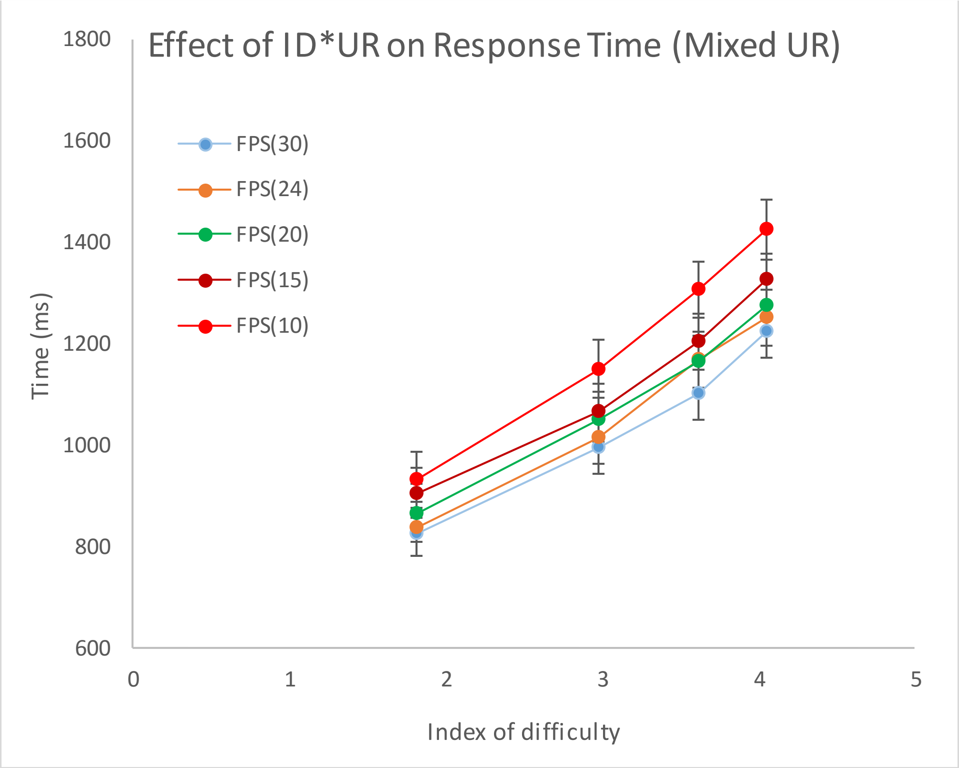

*Figure 12: Effect of ID*UR on response time (mixed UR)*

An additional 2x4x5 mixed-measures ANOVA was used to assess the relationship of condition (blocked or mixed UR) and response time. Different from Sub-study 1, the comparison between Experiment 2a and 2b did not find a significant effect of blocked vs. mixed UR on response time [$F(1, 18) = .733$, $p=.403$, $\eta_p^2 = .039$].

Study 2 discussion

Much like Experiments 1A and 1B in sub-study 1, Experiments 2A and 2B showed that, UR, ID, and consistency of UR had clear effects on response time. There was also a clear relationship between UR level and subjective experience of input device performance, wherein low UR levels negatively impacted users' subjective experience.

General discussion & Future directions

The findings from the four experiments clearly showed that the reduced visual feedback resulting from latency or low updating rate could significantly impact a user' motor performance in a 2-dimensional pointing task and also his or her subjective opinion on the device's usability. More specifically, Experiments 1A and 1B found that increasing latency resulted in longer response time as well as lower subjective rating. Similar effects of reduced updating rate were also observed in Experiment 2A & 2B. Then how well could the users' subjective experience be related to their motor performance?

Consider the effects of visual latency first. A regression analysis was used to assess the relationship between mean response times and mean subjective ratings across all latency levels. Response time was found to be a very strong predictor of subjective ratings [$p<.01$] and it could account for a majority of the variation observed in ratings

[R^2=.94]. As shown below, the value of the coefficient was negative (-0.0055), indicating that participants might mainly rely on the perceived response time to make the usability rating and longer response times were associated with increased difficulty of use and hence lower ratings as the visual latency increased.

$$y=-0.0055(RT)+9.8758$$

Similarly, a regression analysis was applied to the data obtained from Sub-study 2. Again, response time was found to be the single and most powerful predictor of subjective ratings [$p<.05$] and account for 86% of the variation observed in ratings [R^2=.86]. As shown below, as the updating rate decreased, the mean response time increased, leading to increased perception of the difficulty of use and thus reduced ratings.

$$y=-0.0093(RT)+13.2146$$

Although the above models were derived from the data collected in a 2-dimensional pointing task using a mouse, we expect that the findings and models can be generalized and extended to some extent to real-world applications that involve delayed visual feedback and a wide range of motor tasks and input devices. For example, in many virtual-reality (VR) or augmented-reality (AR) applications, a delay in visual feedback is unavoidable because a certain amount of time is always needed to retrieve the data from sensors, update the virtual models, render the graphical effects with sufficient realism, and then transmit the images to the displays like head-mount displays (HMDs). The updating rate is also limited by the computer's ability to visualize complex 3D scenes and graphical effects like reflections, shadows, scattering, motion blur, etc. Moreover, users often perform 3-dimensional motor tasks in immersive VR/AR environments, for example, gesture-based gaming using the Microsoft's Kinect sensor. As such applications are becoming more and more popular, it will be important to quantitatively predict how visual latency and slow updating rate will influence users' performance and experience. Further work may explore this topic. We expect that a similar pattern may be observed regarding the impact of visual latency and slow updating rate on 3-dimensional motor tasks as well as user experience.

The effects of visual latency and updating rate may be examined in more real-world settings. In this study, blocked (Experiment 1a & 2a) or intermixed (Experiment 1b & 2b) presentations were utilized to explore the presence of an adaptation effect in the blocked-presentation conditions. In many real-world applications such as online-gaming or tele-surgery via internet, however, the latency and updating rate may vary from time to time. That is, in order to mimic such situations, latency and updating rate need to vary not only from trial to trial but also within a trail. Further experiments will be needed to examine if our models will still hold up.

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APPENDIX A

SUBJECTIVE PERFORMANCE RATING QUESTIONNAIRE

Session #	

Please complete the following questions on the basis of your experience with the mouse.

1. It was easy to use the mouse to complete the task in this session.
   - [ ] Definitely disagree
   - [ ] Mostly disagree
   - [ ] Neither agree nor disagree
   - [ ] Mostly agree
   - [ ] Definitely agree

2. The movement of the mouse was accurate and precise in this session.
   - [ ] Definitely disagree
   - [ ] Mostly disagree
   - [ ] Neither agree nor disagree
   - [ ] Mostly agree
   - [ ] Definitely agree

3. I would like to rank my overall performance (speed & accuracy) in this session as
   - [ ] 1. Very bad
   - [ ] 1.5
   - [ ] 2. Not too bad
   - [ ] 2.5
   - [ ] 3. Okay
   - [ ] 3.5
   - [ ] 4. Good
   - [ ] 4.5
   - [ ] 5. Very good

4. The cursor on the screen were responsive to my hand motion.
   - [ ] Definitely disagree
   - [ ] Mostly disagree
   - [ ] Neither agree nor disagree
   - [ ] Mostly agree
   - [ ] Definitely agree

5. As compared to my daily experience, I would say, in this session, the mouse worked
   - [ ] 1. Very, very bad

[ ] 1.5
[ ] 2. Not so bad
[ ] 2.5
[ ] 3. Okay
[ ] 3.5
[ ] 4. Good
[ ] 4.5
[ ] 5. Very good

APPENDIX B

ASU IRB HUMAN SUBJECTS RESEARCH APPROVAL

ASU Knowledge Enterprise Development

EXEMPTION GRANTED

Bing Wu
Polytechnic School - HSE Programs
480/727-3716
Bing.Wu@asu.edu

Dear Bing Wu:

On 12/30/2014 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Psychophysical evaluation of gesture-based user interfaces
Investigator:	Bing Wu
IRB ID:	STUDY00002061
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• Sample study information, Category: Recruitment Materials; • Sample demographic questions , Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Consent form, Category: Consent Form; • Sample Questionnaire, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Protocol, Category: IRB Protocol;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 (2) Tests, surveys, interviews, or observation on 12/30/2014.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,
IRB Administrator

cc:

Kyle Brady