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Regular Article

Monitor refresh rate impacts FPS video gamers' perceptions of display 'smoothness' and target acquisition performance

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ABSTRACT

Esports, particularly First-Person Shooter (FPS) games, rely heavily on one's ability to rapidly perceive and respond to visual targets, a skill known as target acquisition. Modern gaming monitors increasingly feature higher refresh rates (up to 360Hz). The current study examined whether FPS gamers can perceptually distinguish between different monitor refresh rates (60Hz, 144Hz, 360Hz) and whether these differences translate to performance improvements in target acquisition tasks. Gamers (N = 101) completed a custom FPS task across three refresh rate conditions. Participants judged the perceived smoothness of display transitions and completed timed trials requiring accurate destruction of on-screen targets. Perceptual data, adjusted for response bias, showed that participants could reliably distinguish between large refresh rate differences (e.g., 60Hz vs. 360Hz), but not between more subtle differences (e.g., 144Hz vs. 360Hz). Changes in target speed modulated perceptual sensitivity, with greater difficulty perceiving latency increases when targets changed from a slow to a fast transition. Performance analyses revealed that reductions in system latency via increased refresh rate led to significant improvements in target accuracy and faster destruction times. Notably, transitions from 60Hz to higher refresh rates improved performance, while shifts from higher to lower refresh rates degraded it. However, performance did not significantly differ between 144Hz and 360Hz conditions. These findings suggest that while FPS gamers can perceive and benefit from refresh rate increases beyond 60Hz, perceptual and performance gains diminish at higher refresh rates. This has implications for hardware optimization in esports, highlighting 144Hz as a possible threshold beyond which further improvements yield marginal returns.

1. Introduction

Esports, defined as the organised, rule-governed, and skill-dominant competitive play of video games, have rapidly emerged as a major form of global entertainment. The number of regular esports followers is projected to exceed 640.8 million by 2026, representing substantial growth from 443 million reported in 2019 (Block & Haack, 2021; Scottmax, 2025). Among esports titles, action video games are particularly prominent due to their high perceptual, cognitive, and motor performance demands, including precise hand–eye coordination, rapid response execution, and continuous decision-making under time pressure.

Within the action genre, First-Person Shooter (FPS) games represent one of the most commercially and competitively successful esports categories. Titles such as Counter-Strike: Global Offensive (CS:GO) ranked among the leading esports globally in 2018 and continue to underpin professional competitive ecosystems (Block & Haack, 2021). A fundamental performance skill in FPS esports is target acquisition, which refers to the ability to rapidly detect, track, and accurately engage opponents from a first-person visual perspective (Liu & Claypool, 2022; Toth et al., 2021). This skill integrates perceptual processing, visuomotor coordination, and fine motor control, and is widely considered a critical determinant of competitive success in FPS gameplay.

During the target acquisition process in FPS games (the majority of

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which are played using a PC with mouse and keyboard inputs), a sequence of human-computer interaction (HCI) events occur that each contributes to the total latency between the appearance and elimination of a target (Spjut et al., 2019). From the time that a target appears on screen, its presence and location must first be perceived by the player. Next, a motor plan is rapidly developed, and a ballistic motor response is produced that moves the computer mouse-hand-arm unit in such a way as to bring the on-screen cursor rapidly towards the target. Finally, as a player homes in on the target, a series of sensorimotor adjustments are made (often referred to as sub-movements) before the player commits to attempting a shot to eliminate the target (Toth et al., 2023; Walker et al., 1993; Thompson, 2007). However, because of the unique human-computer interaction that occurs during video game play, one must also consider the impact that latency contributions, from both the hardware and software used to display targets and process peripheral inputs, have on both player perception and the performance of target acquisition tasks.

Previous work has shown that the monitor is a key component of a gaming PC setup that can affect latency, with refresh rates as low as 10-30Hz significantly hindering target acquisition performance (Chen & Thropp, 2007) and refresh rates up to 60Hz leading to marked performance improvements (Claypool et al., 2006; Janzen & Teather, 2014). With advances in technology, monitors now can provide refresh rates of 144 (most commonly used currently), 240 and even 360Hz for gaming. More recently, studies have been conducted to examine whether newer monitors with faster refresh rates continue to provide performance benefits to users. While early evidence suggests that higher refresh rates can benefit performance on simple reaction time (Murakami et al., 2021) and more complex target acquisition and tracking tasks (Spjut et al., 2019), claims from this initial work are either anecdotal or based on data from a small number of participants. Crucially, the degree to which FPS performance can be enhanced when reducing latency from using higher refresh rate monitors is not well-known (Liu et al., 2023). As refresh rates of up to 360Hz become more commercially available, there remains an appetite to better understand both the ability of users to perceive differences between refresh rates and the performance enhancing potential that higher refresh rates may have for video gamers, given how closely perceptual ability is linked to performance (Proteau, Marteniuk, Girouard & Dugas, 1987). Demonstrating a performance advantage of monitors with ever higher refresh rates will better inform players of the benefits to investing in new monitor technology and help manufacturers understand at what refresh rates benefits begin to saturate.

The purpose of this study is to determine whether action video gamers can perceptually distinguish between monitor refresh rates (60Hz, 144Hz, 360Hz) and whether monitor refresh rates up to 360Hz can enhance performance on a target acquisition task in a cohort of PC action video gamers. We first hypothesised that gamers would be able to perceptually distinguish between all three refresh rates tested. This would be evidenced by perceptual responses to refresh rate changes that significantly differ from chance or guessing. Secondly, we hypothesised that performance on a target acquisition task would improve when performed at higher, compared to lower, refresh rates. This would be evidenced by higher accuracy and faster target destruction times when performing at higher, relative to lower, refresh rates.

2. Methods

2.1. Participants

115 healthy adult participants (97 male)(Age 21.53 ± 4.02 years; mean ± SD) were recruited from the University of Limerick student population. Participants were screened for and included if they had normal/corrected to normal vision and were free from any neurological or neuromuscular disorders. 14 participants were excluded following this screening, resulting in a sample of N = 101. Participants provided written consent prior to participation in the study, which was approved by the University of Limerick, Faculty of Education and Health Sciences Research Ethics Committee in accordance with the Declaration of Helsinki, with the approval number 2022_04_04_EHS, dated August 2025.

2.2. Equipment

Two identical testing stations were used to run the experiment and collect data, each consisting of a gaming PC, an Alienware 25 (Nvidia G-Sync) 1080p 360Hz LCD gaming monitor, Logitech Pro Wireless gaming mouse, and Logitech G513 gaming keyboard. Each PC was equipped with a 3070Ti NVIDIA graphics card, 16 Gb of RAM and Intel i7-8700 3.2 GHz CPU. The gaming mouse on each station was set to a default DPI of 3200.

2.2.1. First person science software

A custom software designed by NVIDIA (Boudaoud et al., 2022) was used to display moving targets at 2 different speeds in a virtual 3D room. Slow moving targets moved at a speed between 2 and 3.5°/second while fast moving targets moved between 5 and 7.5°/second around the environment. Before commencing the task, participants were instructed to adjust the cursor sensitivity of the mouse in the software until they felt they had "good control over the movement of their aim within the environment". The chosen sensitivity was recorded by the experimenter. During the experimental session, participants were exposed to 10 s trials whereby they were required to shoot a green circular target that appeared and moved about on-screen as accurately and quickly as possible. To start each trial, participants were instructed to hover their crosshair (cursor) over a stationary red target in the middle of the environment and press the left shift key on the keyboard, after which this target disappeared, and a moving green target appeared. Participants destroyed the green targets using the left mouse button. One target appeared at a time, with a new target appearing as soon as the previous was destroyed. During each trial, the monitor refresh rate was set to 60Hz, 144Hz, or 360Hz. To objectively test the average system latency associated with each monitor refresh rate, and move beyond theoretical calculations, a Latency Display Analysis Tool (LDAT; a measuring device that accurately detects and measures latency between the mouse click event and associated change in luminance on the physical display using a luminance sensor. Please see https://developer.nvidia.com/nvidia-latency-display-analysis-tool for more information) was used to establish the average latency of the system over 100 inputs (mouse clicks). Fig. 1 shows the average ± SD latency experienced by participants when using monitor refresh rates of 60Hz, 144Hz and 360 Hz (Fig. 1A) as well as the average difference in latency between these combinations of refresh rates (Fig. 1B).

After each trial, participants were asked to indicate whether that trial was presented more or less smoothly (higher or lower refresh rate respectively) than the preceding trial, by pressing either "1" ("more smooth") or "4" ("less smooth") on their keyboard. Participants were exposed to three practice trials before the test blocks to ensure they understood the test. The task consisted of 3 test blocks, each containing 37 trials, with a mandatory 2-min break provided between each block of trials. Trials were presented in such a way that participants were exposed to all combinations of consecutive refresh rates and target speeds across trials within each block (See Fig. 2).

2.3. Procedure

Participants attended the Esports Science Research Lab based in Lero at the University of Limerick for one test session lasting approximately 50 min. Upon arrival, participants completed a demographics questionnaire which captured information regarding their age, sex, gaming experience (how often they spend on average gaming per week and their preferred game genre) and the monitor refresh rate they used with their at-home gaming setup (See Supplementary Table 1). Participants were

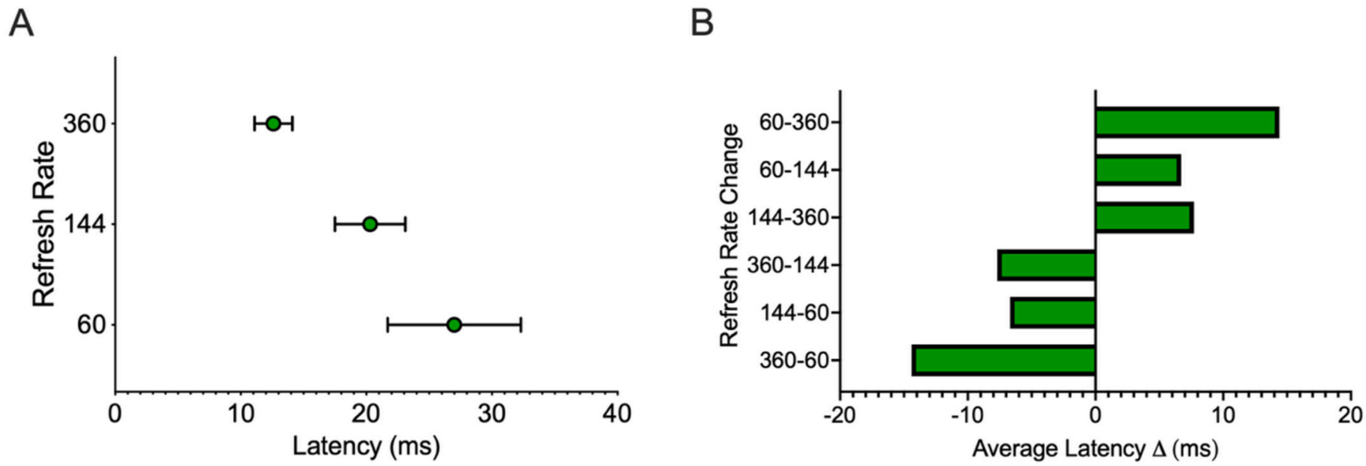

Fig. 1. A) Average latency ± SD across 100 mouse clicks as detected by the LDAT device at each monitor refresh rate. B) Average difference in latency between combinations of the three refresh rates tested in the experiment (60Hz, 144Hz and 360Hz).

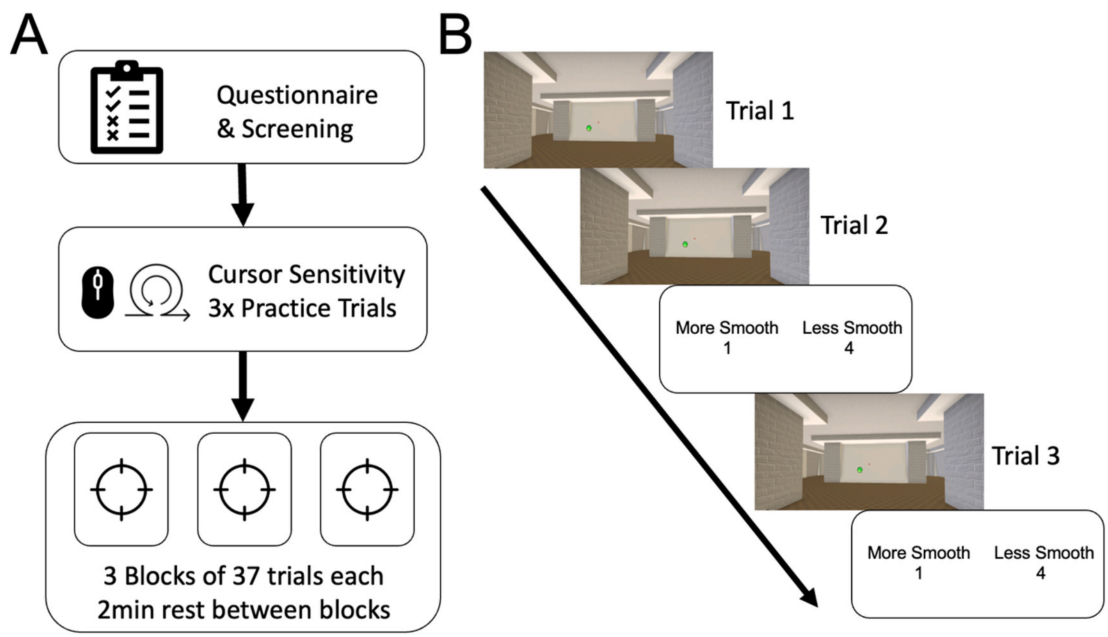

Fig. 2. A) Flow diagram of experimental procedure. B) Example presentation of the first three trials within each of the 3 experimental blocks. Trials differed by their target speed and monitor refresh rates. Consecutive trials were presented at the start of each block, after which participants made their first perceptual judgement (i.e., 'was Trial 2 more or less smooth than trial 1'). Perceptual judgements then occurred after every successive trial (i.e., 'was Trial 3 more or less smooth than trial 2', etc.).

asked to refrain from caffeine 4-6 h prior to participating in the study. Then, participants sat at the testing station, and were briefed on the experiment. They set their in-game cursor sensitivity and were exposed to 3 practice trials where the monitor refresh rate changed from 15Hz to 360Hz across the trials to provide an obvious example of the perceptual task. Participants then completed the three blocks of test trials, with the instruction to destroy the green targets as quickly and accurately as possible.

2.4. Data processing

2.4.1. Perception

Perceptual responses were coded such that perceiving a trial's refresh rate as 'smoother' than what was presented in the previous trial resulted in a score of '1' whereas a perception of 'less smooth' was scored a zero. The average score for each refresh rate and speed change condition across blocks was recorded for each participant. This provided an estimate of the percentage of trials for a given condition that a participant perceived the 2nd trial in that condition as 'smoother' than the 1st trial.

To estimate any response bias among participants regardless of whether refresh rate changed, 0.5 was subtracted from the average response for each condition where the refresh rate did not change between consecutive trials (60-60, 144-144 and 360-360; response average expected to be 50%). This provided an estimate of the response bias above or below guessing for each refresh rate condition where the refresh rate remained constant between trials. Then, for each condition where the refresh rate did change, the response bias corresponding to the refresh rate of the 2nd trial in the refresh rate change condition was subtracted from the response average for that condition. For example, for 360-60 and 144-60 conditions, the response bias determined in the 60-60 condition was subtracted from the average response in each of the 360-60 and 144-60 conditions. Alternatively, for 360-144 and 60-144 conditions, the response bias determined in the 144-144 condition was subtracted from the average response in those conditions. See Supplementary File 1 for data pertaining to 360-360, 144-144 and 60-60 conditions. This normalisation process was performed across the conditions where refresh rates changed from one trial to the next for each target speed change combination (fast-fast, FF; fast-slow, FS; slow-fast, SF; slow-slow, SS). As a result, data for six refresh rate change conditions for each speed change combination remained that each reflected bias normalised perceptions to latency changes between different refresh rate latencies (360-60, 14.4ms increase in average latency; 144-60, 6.7ms increase in average latency; 360-144, 7.7ms increase in average latency; 144-360, 7.7ms decrease in average latency; 60-144, 6.7ms decrease in average latency; 60-360, 14.4ms decrease in average latency).

2.4.2. Performance

Two performance variables were measured for each 10 s trial. Accuracy (ACC) was calculated as the percentage of target hits divided by the number of shots taken while the average time taken to destroy targets during a trial (target destruction time; TDT) was determined as the average time between target appearance and destruction across the targets in a trial. After calculating each variable for each individual trial, the difference in performance for each variable was calculated across consecutive trials and performance difference values for 60-60, 144-144 and 360-360 trials were subtracted from performance difference values in conditions where refresh rates did change (as described above).

2.5. Statistical analyses

All analyses were conducted using SPSS statistical software version 28. Normality of data residuals were verified for each variable using Shapiro Wilk statistics and via investigation of histogram and Q-Q plots. Data outside 1.5 times the interquartile range were excluded from further analyses.

To address the first hypothesis, that our cohort of gamers would be able to perceptually distinguish between all three refresh rates, we first conducted one-sample t-tests to test if the percentage of trials participants responded ‘smoother’ for the second refresh rate was different from 50% (guessing). This was performed for each refresh rate change condition separately for each target speed change condition.

To test whether participants were more sensitive to latency changes when latency increased versus decreased for the same change in refresh rate (i.e., 360-60 vs 60-360), and whether changes in target speed affected latency perception for a given change in refresh rate, we performed a 2-way mixed measures ANOVA to test for differences in the percentage of ‘smoother’ responses, with refresh rate change and target speed change inputted as the within-subjects and between subjects variables, respectively.

To address the second hypothesis, that performance on a target acquisition task would improve when performed at higher compared to lower refresh rates, we performed 1-sample t-tests on target speed pooled ACC and TDT data.

We also performed three 2-way mixed measures ANOVAs on ACC and TDT data with refresh rate input as the within-subjects variable and target speed change as the between-subjects variable. Where sphericity of the data was violated when performing mixed measures ANOVAs, Greenhouse-Geisser degrees of freedom adjustments were applied. Where multiple t-tests or multiple comparisons were used, Sidak adjustments to alpha levels were made and η_p^2 effect sizes are reported.

3. Results

The participants in this study played video games on average 17.70 (±12.34) hours per week, and predominantly played FPS games (73.3% of participants), with the remainder playing MOBA (11.9%), RPG (9.9%) and Racing/Other games (4.9%). They played using monitor refresh rates ranging from 40Hz (n = 3) to 360 Hz (n = 1) with 60Hz (n = 23), 120Hz (n = 10), 144Hz (n = 48) and 240Hz (n = 8) most reported.

3.1. Perception

Results from the series of 1-sample t-tests, used to test whether participants’ perception of refresh rate changes for different changes in target speed were significantly different from guessing (50%), demonstrate that participants could perceive the effect that changes in refresh rates of 360-60, 144-60, 60-144 and 60-360 had on the smoothness of the on-screen display during the task. However, participants could not significantly perceived changes in display smoothness when refresh rates changed between 360 and 144 Hz (Table 1)(Fig. 3A and B).

The two-way mixed measures ANOVA revealed a significant interaction between the magnitude of the perceptual response to changes in Refresh Rate and Target Speed ($F_{(10.254,584.503)} = 7.031$, $p < 0.001$, $\eta_p^2 = 0.164$). Post hoc comparisons demonstrated that changes in target speed influenced perceptions of refresh rate changes *only* for Refresh Rate conditions where the change in refresh rate resulted in an increase in latency (360Hz-60Hz, 144Hz-60Hz and 360Hz-144Hz conditions; see Fig. 3C and D and Fig. 4).

Firstly, the ability to perceive the increase in latency caused by a refresh rate change from 360Hz to 60Hz was not different between when target speed remained fast or slow between trials (FF vs SS conditions; p = 0.431). However, the ability to perceive a 360Hz-60Hz change in refresh rate was significantly weakened when target speed correspondingly changed from slow to fast, compared to when it changed from fast to slow (p < 0.001) or remained fast (FF; p = 0.008). Moreover, the ability to perceive a 360Hz-60Hz change in refresh rate was significantly enhanced when target speed correspondingly changed from fast to slow, compared to when it remained slow (SS; p = 0.006) (See Fig. 4).

For a latency increase resulting from a 144Hz-60Hz change in refresh rate, perception was also significantly weakened when target speed correspondingly changed from slow to fast, compared to when it changed from fast to slow (p < 0.001) or remained fast (FF; p < 0.001). Perception of a 360Hz-60Hz change in refresh rate was significantly enhanced when target speed correspondingly changed from fast to slow, compared to when it remained slow (SS; p = 0.040) (Fig. 4).

Finally, for the latency increase resulting from a 360Hz-144Hz change in refresh rate, perception the latency change was significantly altered when target speed correspondingly changed from slow to fast, compared to all other speed change conditions (all p < 0.032) (Fig. 4).

3.2. Performance

1-sample t-tests, used to test whether participants’ accuracy was significantly altered by the different changes in refresh rate, demonstrated significant accuracy decrements when refresh rates changed from 360 to 60Hz (p = 0.002) or 144 to 60Hz (p < 0.001). Alternatively,

Table 1
1-sample *t*-test results for comparisons of perceptions of display ‘smoothness’ to changes in refresh rates and target speeds across consecutive trials relative to 50% (guessing). p-values <0.05 are in bold font.

	Latency Increase (Less Smoth)			Latency Decrease (Smoother)		
Target Speed Change	360-60 (p-value)	144-60 (p-value)	360-144 (p-value)	144-360 (p-value)	60-144 (p-value)	60-360 (p-value)
Fast-Slow	**<0.001**	**<0.001**	0.252	0.058	**<0.001**	**<0.001**
Slow-Fast	**0.003**	1	**0.002**	**0.021**	**<0.001**	**<0.001**
Fast-Fast	**<0.001**	**<0.001**	0.09	0.675	**<0.001**	**0.009**
Slow-Slow	**<0.001**	**<0.001**	0.294	0.05	**0.002**	**0.001**

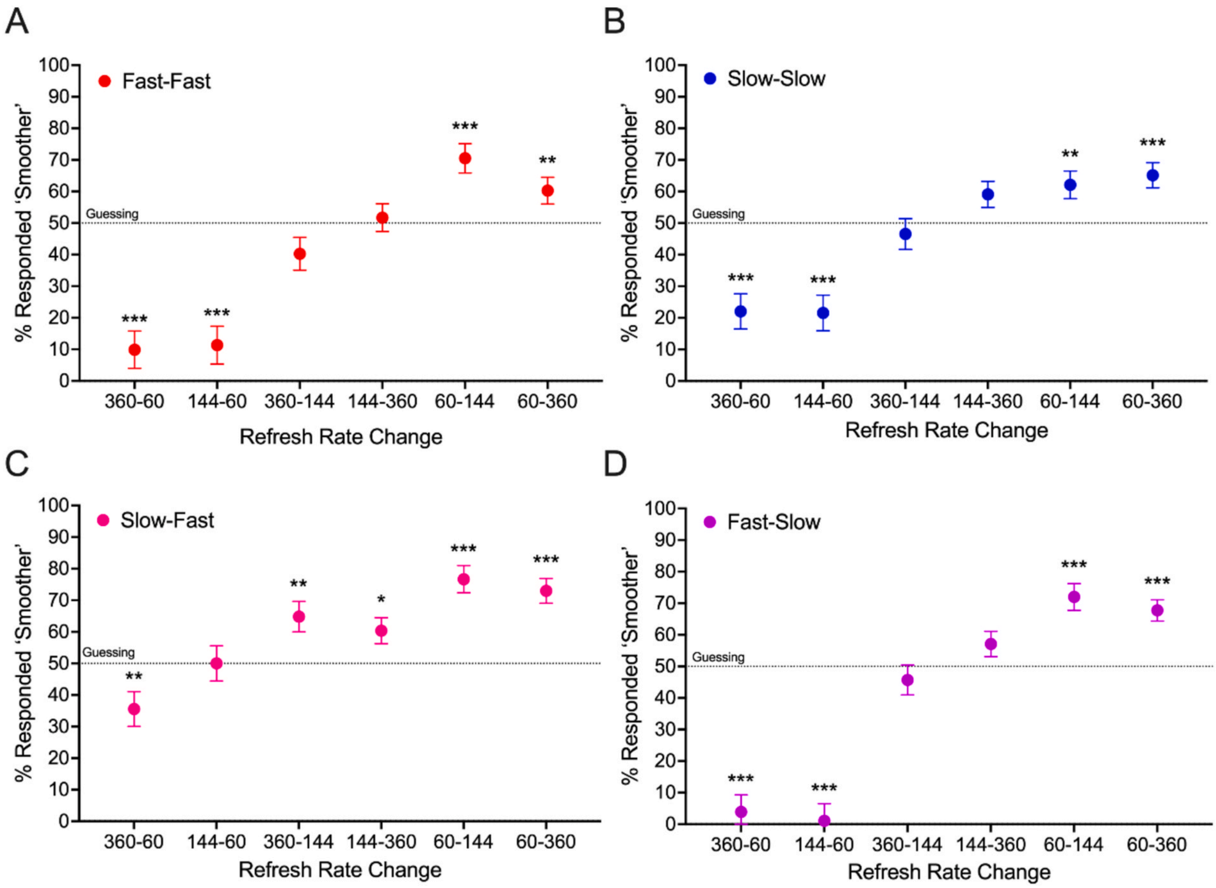

Fig. 3. Average bias-normalised perceptions of display 'smoothness' across changes in refresh rates for each target speed change combination (A: Fast-Fast; B: Slow-Slow; C: Slow-Fast; D: Fast-Slow). *, ** and *** indicate a significant difference in smoothness perception from 'guessing' (dotted line) at the p < 0.5, <0.01 and < 0.001 alpha level. Positive and negative values indicate the second refresh rate in each condition to be perceived as more and less smooth than the first refresh rate respectively.

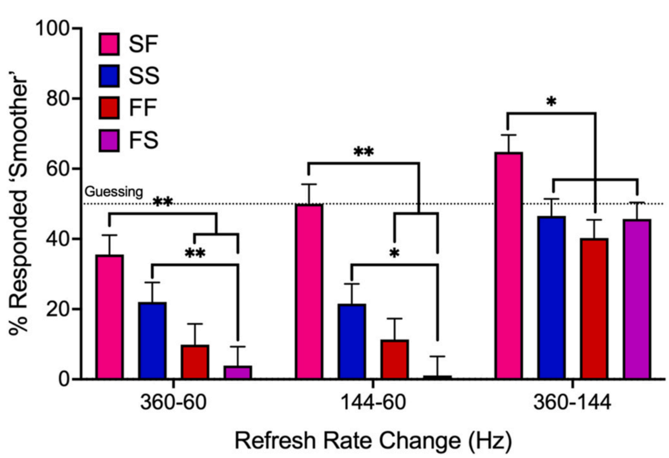

Fig. 4. Average bias-normalised perceptions of display 'smoothness' across target speed change combinations (Fast-Fast, red; Slow-Slow, blue; Slow-Fast, pink; Fast-Slow, purple) for refresh rate changes that resulted in an increase in latency. * and ** indicate a significant influence of target speed on the detection of the latency difference associated with a given refresh rate change at <0.05 and < 0.01 alpha levels, respectively.

60-144Hz ($p = 0.036$) and 60-360Hz ($p < 0.001$) refresh rate changes led to significant improvements in performance accuracy. No significant difference in accuracy was observed for refresh rate changes between 360 and 144 Hz (360-144Hz $p = 0.060$; 144-360Hz $p = 0.401$) (Fig. 5A).

A two-way mixed measures ANOVA revealed a significant main effect of refresh rate change on performance accuracy ($F_{(3.826,\ 654.202)} = 9.523$, $p < 0.001$, $\eta_p^2 = 0.053$). No main effect of target speed change ($F_{(3,\ 171)} = 1.006$, $p = 0.392$, $\eta_p^2 = 0.017$) or interaction was found ($F_{(11.477,\ 654.202)} = 0.947$, $p = 0.496$, $\eta_p^2 = 0.016$). Overall, as latency decreased with changes in refresh rates, target accuracy improved. Specifically, accuracy improved significantly more following a 60-360Hz compared to each of a 360-60Hz ($p < 0.001$), 144-60Hz ($p < 0.001$) and a 360-144Hz ($p < 0.001$) change in refresh rate. Accuracy also significantly improved more following a 60-144Hz compared to 360-60Hz ($p = 0.006$), a 144-60Hz ($p < 0.001$) and a 360-144Hz ($p = 0.002$) change in refresh rate (Fig. 5A). Finally, accuracy significantly improved more following a 144-360Hz compared to a 144-60Hz ($p = 0.049$) change in refresh rate (Fig. 5A).

The 1-sample t-tests used to evaluate whether participants' mean target destruction times (TDTs) were significantly altered by the different changes in refresh rate demonstrated that TDTs were hindered by 360-60Hz ($p < 0.001$), 144-60Hz ($p = 0.107$) and 360-144Hz ($p = 0.004$) refresh rate change conditions. Alternatively, 144-360Hz ($p = 0.018$), 60-144Hz ($p = 0.064$) and 60-360Hz ($p < 0.001$) refresh rate changes led to significant improvements in TDTs. The two-way mixed measures ANOVA performed on mean target destruction times (TDTs) showed a significant interaction effect between refresh rate and target speed changes ($F_{(11.419,\ 441.524)} = 2.340$, $p = 0.007$, $\eta_p^2 = 0.057$) as well as a significant main effect of refresh rate condition ($F_{(3.806,\ 441.524)} = 13.842$, $p < 0.001$, $\eta_p^2 = 0.107$). No main effect of target speed change ($F_{(3,\ 116)} = 0.524$, $p = 0.667$, $\eta_p^2 = 0.013$) was found. Overall, as latency decreased with changes in refresh rates, mean TDTs reduced (see

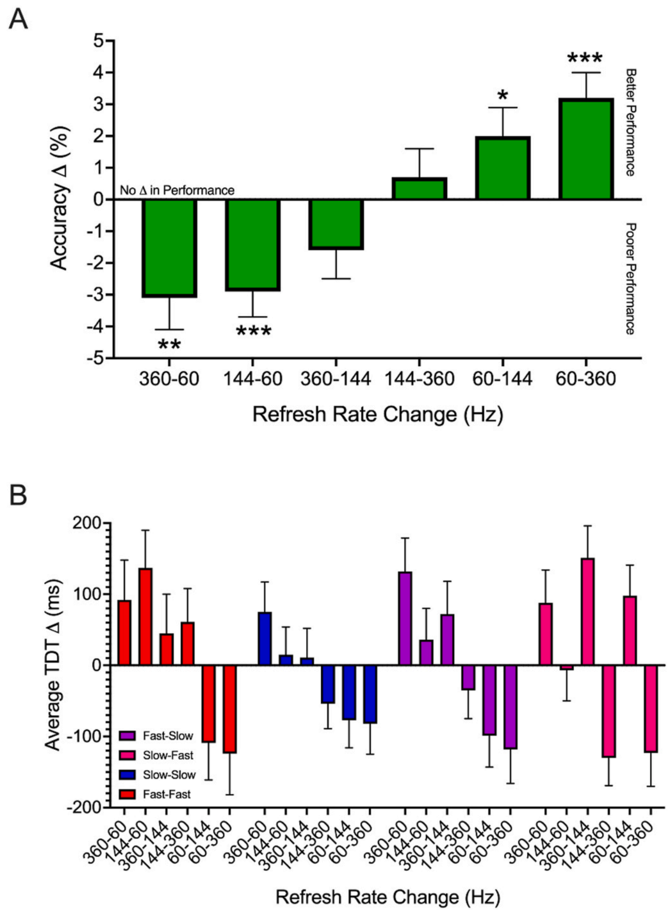

Fig. 5. A) Mean (±SE) change in target accuracy across all consecutive refresh rate trial combinations pooled by target speed change. Positive values indicate a performance decrement across trials while negative values indicate a performance improvement. *, ** and *** indicate significant difference from 1-sample t-tests comparing performance to no change in performance ('0' on the graph) for each refresh-rate change condition at $p < 0.05$, <0.01 and < 0.001, respectively. B) Mean (±SE) change in target destruction times (TDTs) across all refresh rate and target speed change combinations. Positive values indicate a decrement in performance across trials while negative values indicate a performance improvement (reduction in target destruction times across trials).

Supplementary File 2 for a summary of post hoc TDT comparisons) (Fig. 5B).

4. Discussion

This study set out to determine whether action video gamers can perceptually distinguish between monitor refresh rates (60Hz, 144Hz, 360Hz) and whether monitor refresh rates up to 360Hz can enhance performance on a FPS target acquisition task in a cohort of FPS PC gamers. In line with our first hypothesis, we found that gamers could perceptually distinguish between 144Hz and 60Hz, 360Hz and 60Hz, but not between 144Hz and 360Hz monitor refresh rates. Secondly, we found in support of our second hypothesis that gamers' performance on a target acquisition task improved when completing the target acquisition task during higher, compared to lower, refresh rate trials. These findings are discussed in more detail below.

4.1. Perception

Overall, our findings suggest that when engaged in an on-screen gaming task, participants could distinguish between 60Hz and both 144Hz and 360Hz refresh rates. However, participants were not significantly able to determine which refresh rate was 'smoother' between 360Hz and 144Hz. This may be explained by the limits of human visual processing. As can be seen in Fig. 1, the mean difference in latency (measured using the LDAT device) between 360Hz and 60Hz was 14ms, while this difference was only 6.7ms between 60Hz and 144Hz, and 7.7ms, and between 144Hz and 360Hz. As demonstrated from psychophysical studies in humans, perception of complex visual scenes can be made in under 150ms, with stimulus presentation times as low as 10ms (Hegde, 2008; Habekost et al., 2013). The fact that the latency difference experienced when transitioning between 60Hz and 360Hz is above this 10ms threshold, but is below the 10ms threshold when distinguishing between 144Hz and 360Hz (7.7ms), may be why there is a lack of perceptual certainty between 144Hz and 360Hz. However, participants were able to distinguish between 144Hz and 60Hz refresh rates, which in this study, corresponded to system latencies of 20.3ms and 27ms respectively, and a mean latency difference of only 6.7ms. However, the fact that participants could distinguish between the 6.7ms average latency difference and not the 7.7ms difference may be further explained by accounting for the variance of latency measurement across the 60Hz (5.3ms), 144Hz (2.8ms) and 360Hz (1.5ms) refresh rates. Considering the possible combinations of latency difference in any two trials where the refresh rate was altered between 60Hz and 144 Hz, the actual experienced latency difference could be as high or higher than 36ms (system latency of 44.4ms (Mean + 3SD) for 60Hz and 11.9ms (Mean - 3SD) for 144Hz). However, this latency difference between 144Hz and 360Hz would only maximally span 11.6ms, near the abovementioned threshold of 10ms and thus, not be significantly perceived by participants in this study.

Interestingly, we noticed that changes in target speed did influence perception of changes to refresh rate, specifically when refresh rate changed from lower to higher latency. When target speed increased (SF) between two trials, participants perceived the second trial's higher latency refresh rate as smoother than they otherwise would have. Alternatively, when target speed decreased (FS) between two trials, participants perceived the higher latency refresh rate as less smooth than they otherwise would have (Fig. 4). This may be due to a recency bias that exists when making perceptual judgements in a forced-choice paradigm, where participants must employ their working memory to alter their attention to judge the latest pair of consecutive trials. In this way, participants may be more greatly influenced by changes in target speed when making perceptions at higher latency refresh rates (60Hz). Another plausible explanation for the reduced sensitivity to latency increases following slow to fast target transitions may be that abrupt increases in target speed shift the visuomotor system toward more prediction-dominant control. Fast-moving targets increase reliance on internal forward models that extrapolate target position to compensate for inherent sensorimotor delays, thereby reducing dependence on online visual feedback (Wolpert & Ghahramani, 2000). Under these conditions, modest increases in display latency may be perceptually absorbed by predictive mechanisms shifting responses to be more biased by target speed. Additionally, target speed changes may be introducing 'visual noise' that participants must allocate attentional resources towards, elevating cognitive load and hindering perceptual judgements. This would be consistent with capacity-limited accounts of attention (Lavie, 2005). Faster motion also significantly increases sensorimotor variability and corrective sub-movements, introducing greater internal noise into the visuomotor loop, which can further reduce sensitivity to external temporal changes (Harris & Wolpert, 1998). Together, these mechanisms may provide a coherent explanation for why latency increases are harder to detect following slow to fast transitions. However, more work is required to explore why this effect was only observed during changes in refresh rates that resulted in an increase in latency.

Finally, previous work has identified that as task expertise increases, sensory-motor integration appears to be more robust, such that sensory-motor perturbations in experts can actually lead to initially greater performance deficits when compared to novice or lower skilled performers (Proteau, Marteniuk, Girouard & Dugas, 1987). Considering this, it may be the case that participants within our sample with more gaming experience show stronger perceptions to changes in monitor refresh rate latency. To test whether a participant's gaming experience influenced their perception of the refresh rate changes in this study, we performed a Pearson correlation between perceptual responses at each refresh rate change condition and participants' reported hours of gaming per week. No correlation was significant (lowest $p = 0.137$), and all correlations were weak (largest $r = 0.113$). However, the number of hours one plays video games per week may not necessarily reflect expertise and future work could look to examining the effect that more appropriate markers of expertise among players in a particular gaming have on perceptions of system latency due to monitor refresh rate.

4.2. Performance

Target acquisition performance during each 10s trial was measured via accuracy and target destruction times. Interestingly, changing monitor refresh rates from 60Hz to 144Hz or 60Hz to 360Hz led to significant accuracy improvements over 3% (Fig. 5A), and TDT reductions of over 100ms (Fig. 5B). To provide context, in a previous study investigating shooting performance improvements among elite Valorant players following 1 week of training, accuracy improvements were only as high as 6.54% (Roldan & Prasetyo, 2021). Here, we see that merely changing one aspect of hardware (the monitor refresh rate) led to an immediate 3% increase in accuracy (Fig. 5A), half of the gains observed in a group of elite players following a week of training. In a study by Toth and colleagues (2023), target destruction times improved in lower skilled gamers by approximately 100ms over the course of 5 days of training on a target acquisition task for 10min per day. This is the same improvement immediately observed when performing the same type of task with a 360Hz compared to 60Hz refresh rate in this study (Fig. 5B). These improvements are functionally meaningful and corroborate previous work highlighting the importance that reductions in system latency can have on gaming tasks requiring precise and rapid responses (Claypool & Claypool, 2007; Claypool, Claypool & Damaa, 2006). The fact that improvements observed as a result of increasing refresh rate from 144 to 360Hz were not significant may result from a saturation of latency-associated performance improvements after 144Hz or due to participants largely being unable to perceive the difference between these refresh rates (Fig. 3), although more work is necessary to confirm this hypothesis.

4.3. Limitations and future directions

There are a few noteworthy limitations that we draw the reader to that may facilitate future research in this area. Firstly, perception in this study was evaluated using a forced-choice paradigm that involved a working memory component not dissimilar to that evaluated during a 1-back N-back task (Jaeggi et al., 2010; Colzato et al., 2013). Therefore, additional less cognitively demanding perceptual paradigms could elucidate stronger perceptions to changes in refresh rates among participants. Moreover, the perceptual task in this study was also concurrently administered while participants attempted to achieve a high performance on the task. While this was more ecological and easier to administer within a timeframe suitable to participants in this study, future paradigms that separate the perceptual and performance components may identify greater perceptual and/or performance differences associated with refresh rate latency changes. Secondly, only three frame rates were tested in this study. The addition of additional frame rates could help confirm more resolutely perceptual and performance improvement saturation points, a relevant marker for gamers and manufacturers to know where to halt the allocation of resources in the search for lower latency. Thirdly, we note that our sample of participants comprised amateur gamers, who had limited exposure with 360Hz monitors. This lack of experience with lower latency monitors could have meaningfully affected our sample's ability to distinguish between 144Hz and 360Hz refresh rates. It would be important for future work to address whether the perceptual ability of elite/expert gamers, with more experience with lower latency hardware, is enhanced relative to an amateur cohort. Finally, as mentioned previously, future research should look to testing the effect of adding or removing latency at additional points along the human computer HCI loop on gamer perception and performance.

5. Conclusion

Overall, this study demonstrates that monitor refresh rate is not merely a matter of visual preference but a meaningful performance determinant. Across a large cohort of action video gamers ($N = 101$), participants reliably discriminated between refresh rate latencies approaching the temporal limits of human visual perception. Crucially, increases in refresh rate produced measurable gains in target acquisition performance equivalent in magnitude to those typically achieved after a full week of dedicated training in experienced gamers. These findings underscore the substantial and immediate impact that display hardware can have on perceptual and motor performance. Accordingly, we not only corroborate prior evidence on the perceptual benefits of higher refresh rates but extend it by quantifying its functional relevance for esports performance and broader human–computer interaction contexts.

CRediT authorship contribution statement

Adam J. Toth: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft. **Joohwan Kim:** Conceptualization, Methodology, Writing – review & editing. **Josef Spjut:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Ben Boudaoud:** Conceptualization, Methodology, Writing – review & editing. **Sophie Cunneen:** Data curation, Formal analysis, Writing – original draft. **Mark J. Campbell:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of the use of AI assisted technologies

The authors declare that no AI assisted technologies were used during any stage in the preparation of this article.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Mark Campbell reports financial support was provided by Research Ireland. Joohwan Kim, Ben Boudaoud, Josef Spjut reports a relationship with NVIDIA Corporation that includes: employment and equity or stocks. N/A If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssaho.2026.102774.

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