Effects of Computer Mouse Lift-off Distance Settings in Mouse Lifting Action

Munjeong Kim
moondoong@dgist.ac.kr
SID Lab, DGIST
Daegu, Republic of Korea

Sunjun Kim*
sunjun_kim@dgist.ac.kr
SID Lab, DGIST
Daegu, Republic of Korea

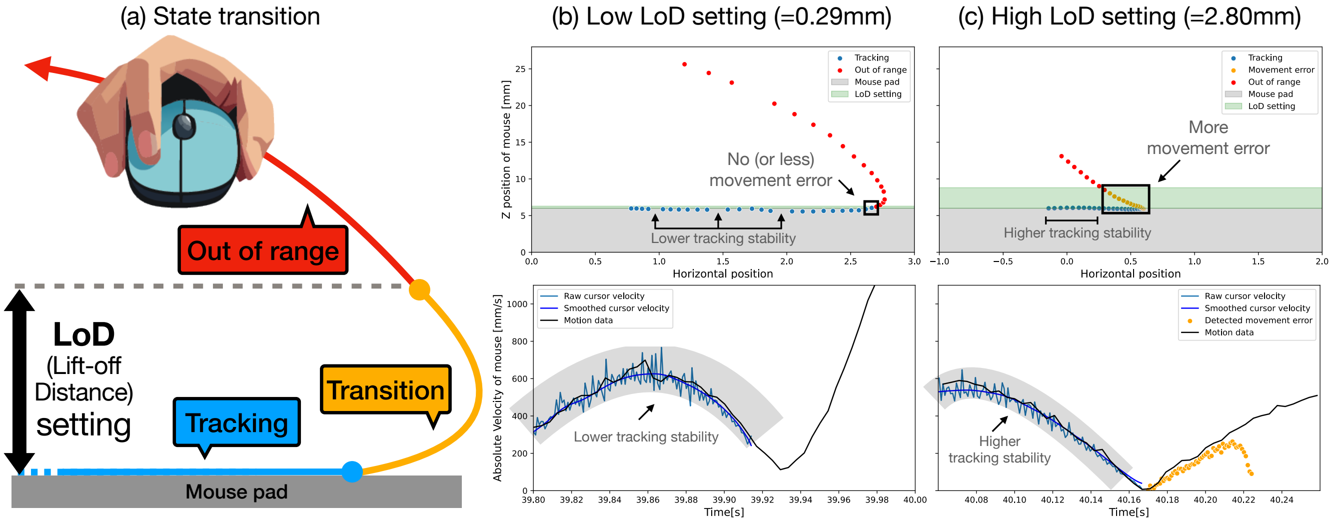
(a) State transition (b) Low LoD setting (=0.29mm) (c) High LoD setting (=2.80mm)

Figure 1: (a) State transition from *tracking* to *out-of-range* during mouse lifting action. Lift-off Distance (LoD) setting determines the amount of *transition* state, which is the state when the mouse device is actually off the surface but still reporting the movement data. (b) When the LoD is low, the unintentional movement error is low (upper), while tracking stability is poor (lower). (c) When the LoD is high, more unintentional movement error is detected during state transition (upper), yet exhibiting enhanced tracking stability (lower).

ABSTRACT

This study investigates the effect of Lift-off Distance (LoD) on a computer mouse, which refers to the height at which a mouse sensor stops tracking when lifted off the surface. Although a low LoD is generally preferred to avoid unintentional cursor movement in mouse lifting (=clutching), especially in first-person shooter games, it may reduce tracking stability. We conducted a psychophysical experiment to measure the perceptible differences between LoD levels and quantitatively measured the unintentional cursor movement error and tracking stability at four levels of LoD while users performed mouse lifting. The results showed a trade-off between movement error and tracking stability at varying levels of LoD. Our findings offer valuable information on optimal LoD settings, which could serve as a guide for choosing a proper mouse device for enthusiastic gamers.

CCS CONCEPTS

• **Human-centered computing** → **Pointing devices**; **User studies**; **Laboratory experiments**; **Pointing**.

KEYWORDS

Mouse, Pointing, Lift-off Distance, LoD, Gaming, User Performance, Mouse lifting, Clutching

ACM Reference Format:
Munjeong Kim and Sunjun Kim. 2024. Effects of Computer Mouse Lift-off Distance Settings in Mouse Lifting Action. In *The 37th Annual ACM Symposium on User Interface Software and Technology (UIST '24), October 13–16, 2024, Pittsburgh, PA, USA.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3654777.3676442

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*Corresponding author

UIST '24, October 13–16, 2024, Pittsburgh, PA, USA

ACM ISBN 979-8-4007-0628-8/24/10
https://doi.org/10.1145/3654777.3676442

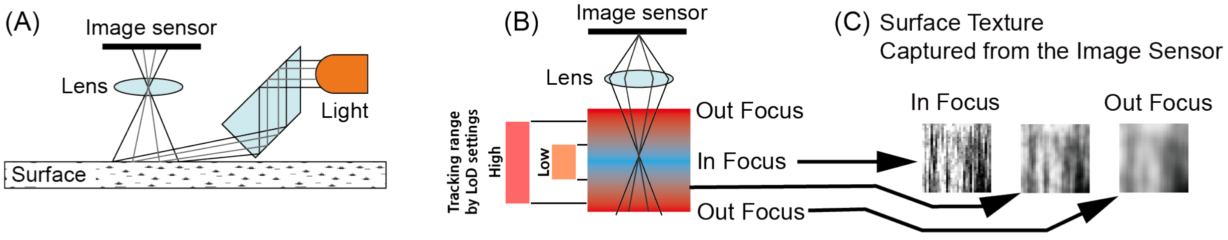

Figure 2: (A) Image sensing structure of an optical displacement sensor. (B) Illustration of the focused zone of the sensor optics. Based on LoD setting, the thresholds for the tracking range is adjusted. With a low LoD setting, the tracking range is narrower, which only accept high-contrast in-focus surface images only. (C) Image quality degradation from the surface in focus to the out focus region.

1 INTRODUCTION

Computer mice have been one of the crucial input devices for computer gaming. Naturally, the search for optimal performance of a mouse device has been an important issue, especially for competitive gamers. Mouse design parameters can affect user performance and comfort, such as weight [8, 9, 28, 29, 43, 49], shape [19, 20, 23, 24, 34], hand and arm posture [10, 17], sensor characteristics (dpi and sensitivity [4, 6, 7, 44], polling rate [14, 18, 36, 46], etc.) and sensor position [25].

In this study, we focus on an unexplored gaming mice parameter known as the lift-off distance (LoD), which is the height at which a mouse sensor stops tracking when lifted off the surface. Lift-off distance (LoD) is an essential factor in *lifting* or *clutching* [4, 6] action, which indicates lifting the mouse to adjust its position on the mousepad [35]. A low LoD is generally preferred, typically less than 3 mm, as it is believed to prevent unintentional cursor movement errors during lifting [39] especially for first-person shooter (FPS) gamers. However, setting the LoD too low may hinder tracking stability. The distance between the sensor and the tracking surface may change due to soft mousepad deformation, subtle irregularities on the desktop surface, and the presence of micro dust under the mouse. If the LoD setting is too low, a slight deviation from the optimal condition will reject the sensor reading (see Figure 2).

Therefore, the LoD setting is a trade-off between tracking stability and unintentional movement error in lifting action, and the optimal LoD setting is the balanced point between them. Finding the optimal LoD of a mouse device is considered essential to achieve the best gaming performance [16, 39, 50].

However, despite its significance, there is limited public information from academia and industry on the quantitative effect of LoD on mouse performance. To our knowledge, no scientific studies have been conducted to assess how different levels of LoD affect user perception and pointing accuracy, and there is also a lack of a standardized LoD measurement methodology. Therefore, the majority of the references cited in this paper are from nonacademic sources such as online forums and articles, which are anecdotal and may not be archival for the long term.

In this paper, we systematically investigated how changing in lift-off distance (LoD) settings affects mouse performance. Our main contributions are:

- We suggested an accurate and repeatable method for measuring LoD (Section 3) and the proposal of stability/error metrics (Section 4.2.3, 4.2.4).
- We conducted experiments to present empirical data on user perception and measurements at different LoD levels (Section 4.1, 4.2).
- We defined LoD problem as a trade-off between tracking stability and unintentional movement error in lifting action (Section 5).
- We suggested a method for finding the optimal LoD setting based on the data (Section 5).

2 RELATED WORK

Various mouse design parameters can affect user performance and comfort in gaming. This section provides an overview of the current state of research on these parameters, including mouse weight, shape, grip style, and sensor characteristics.

Weight: Proper mouse weight can increase movement efficiency and reduce muscle activity. Recent research favors minimizing mouse weight (around 60 – 80 g), which could improve gaming performance and reduce fatigue [27–29, 49], while Chen et al. found that muscle activities showed a V-shaped tendency, and the lowest muscle activity was observed with the mouse weight of 130 g [8].

Shape and Grip Style: Shape and grip style affect user comfort and performance [23]. Compared to the conventional mouse, the slanted and vertical shape, a.k.a. ergonomic mouse, offers better wrist posture, but reduces pointing performance [19, 34]. The position of the mouse and the posture of the arm also affect muscle activity and carpel tunnel pressure [10, 24]. Different grip styles (palm, claw, fingertip) are also believed to change the comfort and task performance. The literature on arm posture implicitly suggests that grip style could change muscle activity; however, no direct research on grip style has been conducted.

Sensitivity: The effect of sensitivity (more generally control-display gain) on pointing performance has been extensively investigated [4, 6, 7, 44]. Low sensitivity requires larger physical movements; therefore, reducing the performance of pointing on large screens [6] but allows more precise control on small targets. For FPS games, 0.9°/mm (=400 mm/360°) was found to achieve the best performance, within the optimal recommended range from 0.45°/mm to 1.8°/mm (=800 mm/360° – 200 mm/360°) [4].

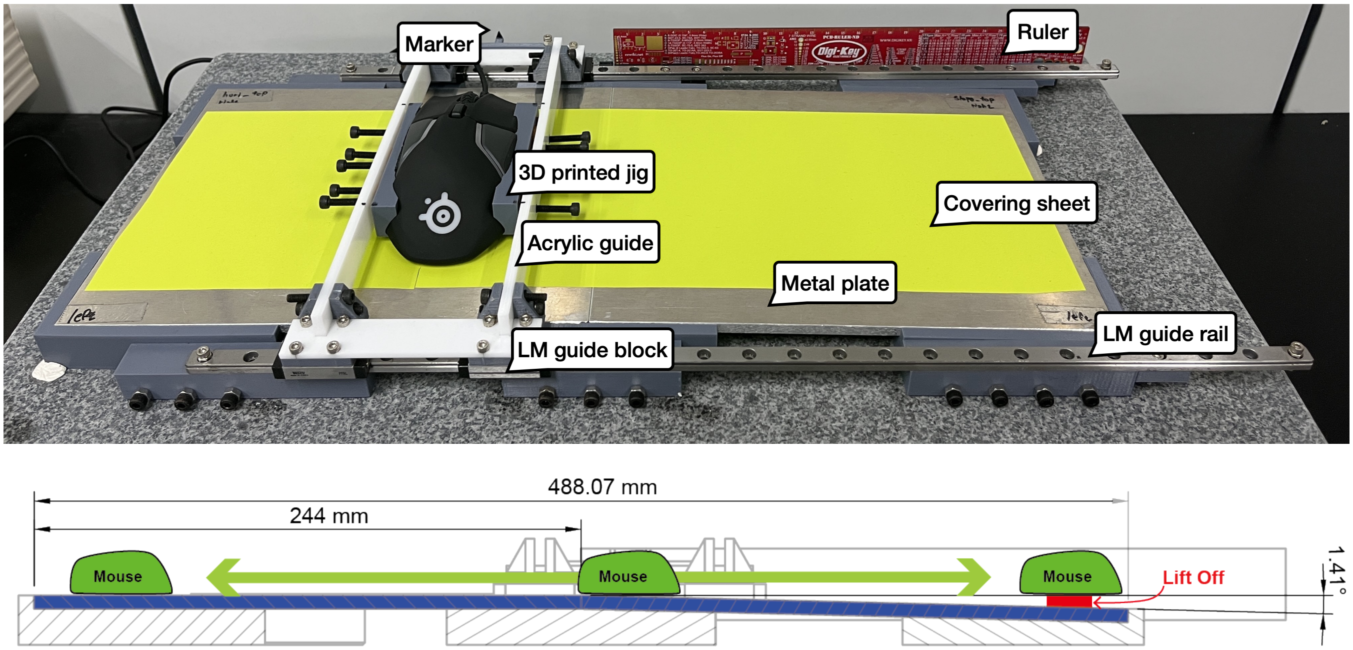

Figure 3: Design of mouse LoD measurement jig. A mouse is fixed to the rail that moves horizontally. As the mouse moves to the right, the base (blue) is slanted downward to increase the distance between the mouse and the surface. The precise height of the mouse could be calculated from the position of the mouse where the cursor stops and moves again while moving it.

Polling Rate: The effect of the polling rate is prominently translated into a matter of latency from 0.125 ms@8000 Hz to 8 ms@125 Hz [46][1]. The pointing performance of the system is adversely affected by increased end-to-end latency [14, 36], which begins to affect from 16 ms [14]. In addition to latency, the asynchrony between the refresh rate of the display and the mouse polling rate could induce jitter [1], and a higher polling rate is favored to reduce it [18].

IPS and Maximum Acceleration: Sensor manufacturers often promote the performance of a high-end mouse in IPS (inches per second) and maximum acceleration capabilities. They indicate the maximum speed and acceleration possible that can maintain the surface tracking. Any mouse sensor with >250 IPS and >20 G rating could outperform human limitations [11], and modern mouse sensors will rarely have performance problems [12].

LoD: In academia, there is a lack of empirical studies and standardized measurement methodologies to understand the Lift-off Distance (LoD) and its impact on user interaction and performance in gaming environments. Instead, there are active discussions in the gamer communities.

Gamers prefer to keep the level of lift-off distance (LoD) low, and they invented several tweaks to lower the LoD: use thicker mouse feet to raise mouse height [38], attach a tape to reduce the amount of light from the sensor (called the *tape trick* [40]), and change the type of mousepad surface [15]. In contrast, some argue that the impact of LoD on gameplay is minimal. For example, Rocket Jump Ninja, a prominent figure in FPS gaming communities, has claimed that LoD does not cause much cursor movement when lifting due to the low sensitivity [33] that FPS players usually set. For measuring LoD, users often use *CD*s or *DVD*s as a unit of an LoD measurement, which is 1.2 mm per disc [15, 26, 37]. They measure the number of discs that the mouse stops tracking as a unit. For example, 1 – 2 DVDs (= 1.2 – 2.4 mm) are generally considered acceptable.

3 LIFT-OFF DISTANCE (LOD) SENSING METHODS AND MEASUREMENT

Modern computer mice utilize optical displacement sensor modules consisting of a light source, a two-dimensional array image sensor, and optics (see Figure 2). The lateral displacement of the module can be sensed by computing the cross-correlation of two consecutive images captured from the sensor. However, the mouse sensor lacks the ability to measure the vertical distance from the surface directly.

An explicit way to control mouse LoD is to employ a separate distance sensor, such as in the SteelSeries RIVAL 600 and EVGA X17 models. This dedicated distance sensor provides a precise LoD control with good accuracy. However, this requires additional cost and increased complexity in device manufacturing, leading to a small number of mouse models choosing this approach.

As an indirect control of LoD, a common approach is the SQUAL (Surface QUALity) based method. As shown in Figure 2, the optics has a fixed focal point and limited depth of field in a range of only 2 – 3 mm. When the tracking surface moves away from the optimal

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[1] Please note that processing and display latency will be added to the mouse latency in the end-to-end latency.

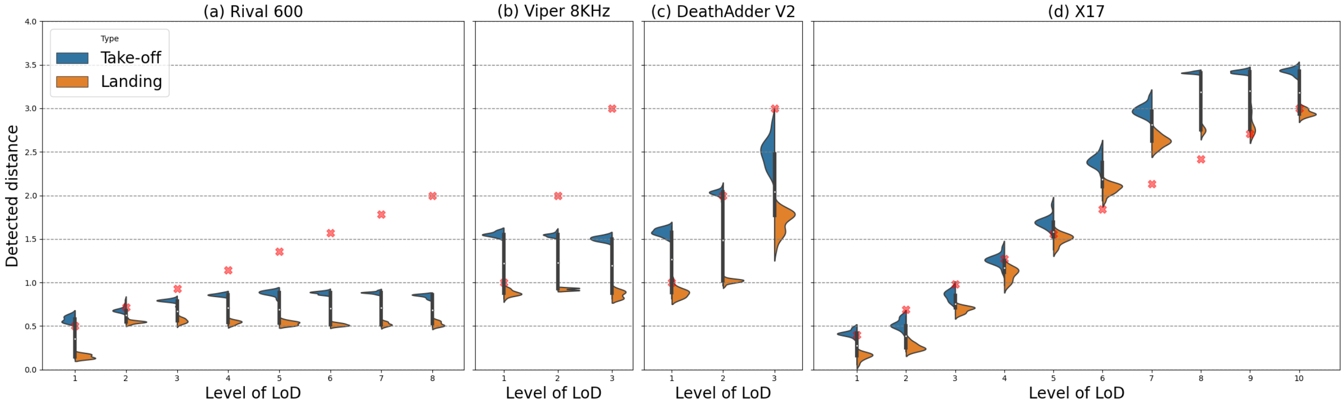

Figure 4: Result of measured LoD during Take-off (=moving right) and Landing (=moving left) using the LoD measuring jig. We measured all available LoD settings levels for four mice, 20 take-off and landing points for each. From the left, (a) RIVAL 600, (b) Viper 8KHz, (c) DeathAdder V3, and (d) X17. The red ×-markers are the claimed LoDs of the device, and the violin plots shows the distribution of the actual LoD measured.

distance, the captured image becomes out of focus, which blurs the surface image. SQUAL measures the prominence of surface features, with higher values corresponding to crisp and in-focus images, and lower values indicating defocused images. Sensors stop tracking when SQUAL falls below a certain threshold, and LoD can be controlled by adjusting the SQUAL threshold value. Higher LoD corresponds to lower SQUAL thresholds and vice versa.

For our experiments, we required a mouse with precise LoD control. While there are numerous commercial mice that advertise adjustable LoD, specific measurements of their LoD have not been publicly available. Therefore, we built a precision measurement jig ourselves for an accurate LoD assessment.

As shown in Figure 3, precision LM guides and two Kobe aluminum metal plates (flatness of $0.2mm/m$) were installed on a calibrated reference plane made of granite. The left plate was mounted flat and the right plate was slightly slanted about $1.41°(\sin\theta = \frac{1}{40})$. A cover sheet was applied to both plates that provides micro-texture for the mouse sensor. The mouse was fixed to the LM guide blocks using a 3D printed jig that perfectly fits the mouse shape, and the bottom of the mouse mated with the surface of the left plate.

While sliding the mouse, a high-speed camera (SONY DSC-RX100M5A, 960 frames per second) captured the cursor's movement on the screen and the marker on the ruler simultaneously. Sliding the mouse to the right makes the distance from the mouse to the surface gradually increase linearly, up to 6 mm, and the position where the cursor stopped (=*take-off* point) was recorded. Similarly, the point at which the cursor started to move again (=*landing* point) was recorded while the mouse moved to the left. The distance between the mouse sensor and the surface could be calculated as $LiftDistance = tan(1.41°) \times MarkerPosition$.

We measured four LoD adjustable mice: two SQUAL-based (RAZER DeathAdder V2 and RAZER Viper 8KHz) and two distance sensor-based (SteelSeries RIVAL 600 and EVGA X17) LoD sensing mice. Among the devices tested, EVGA X17 exhibited superior performance in the range of 10 LoD levels from $0.4mm$ to $3.0mm$ (see Figure 4); therefore, we used this for the rest of the experiments.

4 EXPERIMENT

To understand how LoD settings affect pointing experiences, a psychophysical LoD perception experiment and target click (TC) test for quantitative error measurements were performed. For the apparatus, a desktop computer (Intel Core i9 9900, 32 GB RAM, NVIDIA GeForce RTX 2060 SUPER) with a gaming-grade monitor (ASUS ROG SWIFT PG259QN, 24.5 inch, 1920 × 1080 px, 360 Hz refresh rate) and a large mouse pad (Steelseries Qck HEAVY, $450mm \times 400mm \times 6mm$) was used with the EVGA X17 mouse.

LoD level was set as an independent variable: LoD levels of 1, 3, 5, and 7 (0.29, 0.77, 1.60, and 2.80 mm in measured LoD, respectively) as shown in Figure 4d. These levels could provide a wide range of LoD while keeping the number of tested conditions manageable. We label them LoD1, LoD3, LoD5, LoD7 in the rest of the paper.

In the both experiments, in the beginning, participants were asked to read and sign a consent form, then we introduce what LoD is, and then explain the experimental procedure. After the tests, we asked for the subjective opinion of the preferred LoD levels, and the experiment ended. The University's Internal Review Board (IRB) approved the entire procedure of this study.

4.1 LoD perception test

The first experiment was a psychophysical test to measure the ability of FPS players to discriminate between different levels of LoD. The ISO 4120:2021 triangle test method [22] was adopted.

4.1.1 Participants. We recruited participants who play games for at least four hours a week using a computer mouse, right-handed, and between the ages of 19 and 50. From a local university, 27 participants were recruited. Three participants with the shortest time playing the FPS game per week based on the demographic survey were excluded (for counterbalancing), and the remaining 24 participants joined the experiment. They were compensated 15,000 KRW (≈ 11 USD) each for their participation.

Table 1: The results of LoD perception test ($N = 24$).

Compared setting level Difference of LoD (mm)	LoD1&LoD3 0.48	LoD3&LoD5 0.83	LoD5&LoD7 1.20	LoD1&LoD5 1.31	LoD3&LoD7 2.03	LoD1&LoD7 2.51
Correct responses (N)	11	10	6	18	16	16
α-risk	= 0.2	-	-	= 0.001	= 0.001	= 0.001

There were 2 women and 22 men (between 19 and 28 years old, 22.04 ± 2.74) who play the FPS game for 4.38 hours a week on average. Only 2 out of 24 participants knew about LoD and only one responded that they tuned the LoD setting.

4.1.2 Task and procedure. In the triangle test, one trial consists of three stimuli, called the *triad*: two stimuli had the same LoD and one stimulus was different from the others. For each stimulus, one of the four levels of LoD was set, then participants were given 45 seconds to freely interact within the 'Countryside' map of AIMLABS[2], which simulates an FPS game environment that allows one to move around, aim, and shoot random targets without a specific goal assigned. Time constraints were established to restrict the use of additional tactics to distinguish the mouse beyond the intuitive recognition of LoD [3, 31]. Each participant examined all three stimuli sequentially in random order and was asked which had a different LoD from the others they thought of. They were forced to choose one, even in the case where the stimuli were indistinguishable.

During the tests, the interaction between the participants and the experimenter is strictly minimized; the experimenter only sets the LoD triads blindly from the participants. Each participant tested six triads[3] made from four levels of the LoD. The presentation order of the six triads was counterbalanced across the participants using a balanced Latin square design [45]. Within a triad, the stimuli order[4] was randomly assigned. Therefore, 6 (triads) × 24 (participants) = 144 triangle test results were collected.

4.1.3 Result. ISO 4120:2021 [22] triangle test defines a perceptible difference between samples if the number of correct answers is equal to or greater than a certain number determined from the total number of trials. From 24 triads, 13, 15, and 16 (equal or more) correct answers are required to conclude that there is a detectable difference between stimuli with α-risk levels of 0.05, 0.01, and 0.001 respectively.

Table 1 shows the number of correct answers in each triad consisting of two LoD levels, and their corresponding α-risk level in the triangle test. The triads are ordered by the difference in measured LoD between the levels. Participants could not distinguish two LoD settings with differences of up to 1.20 mm, and all triads with a LoD difference greater than 1.31 mm were distinguishable.

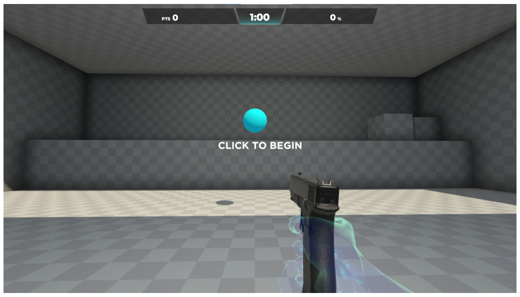

Figure 5: Screenshot of AIMLABS SPIDERSHOT 180 (ULTIMATE) task.

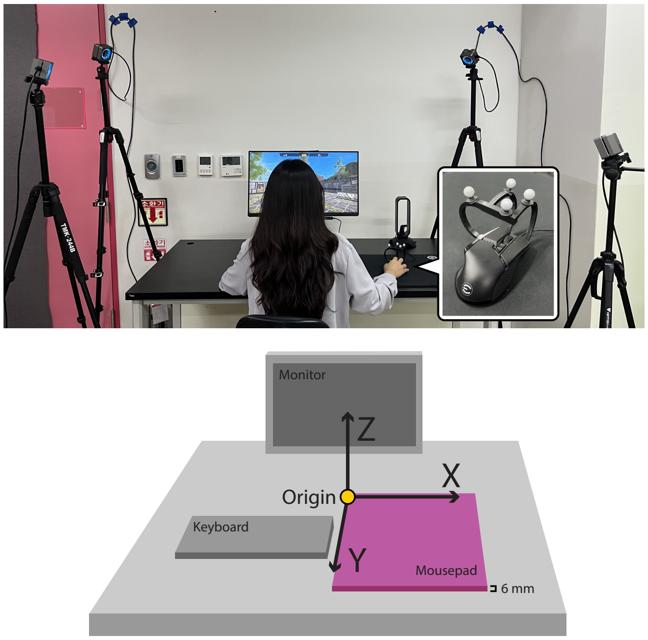

Figure 6: Target click test setup. Four markers were glued onto a 3D printed fixture mounted on the X17. The fixture was designed to avoid any obstruction with hand movements. The physical motion of the mouse was then monitored by four motion capture cameras. The origin point was set on the desk surface at the top left corner of the mousepad.

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[2] A online training platform to enhance player's core FPS aiming skills.

[3] When constructing triads using 4 level of LoD, the six possible pairs exist (1&3, 1&5, 1&7, 3&5, 3&7, 5&7).

[4] The possible order of stimulus within a triad is six. For example, with LoD1 and LoD3, there are six possible sequences (113, 131, 311, 133, 313, 331).

4.2 Target click (TC) test

In the second experiment, the trade-off between unintentional cursor movement error (Section 4.2.3) and tracking stability (Section 4.2.4) was explored. In the following, for a statistical analysis, we performed Repeated Measure Analysis of Variance (RM-ANOVA) on JASP v0.17.3. Greenhouse-Geisser correction was applied whenever the data violated the sphericity assumption. As a post hoc test, a pairwise *t-test* with Bonferroni corrections was performed. The results of the post hoc test are illustrated in the figures by the lines between the conditions. For the p-values, we annotated $* = p < .05$, $** = p < .01$, $*** = p < .001$. The effect sizes are represented with partial eta squared. All results are reported in the form of marginal mean ± standard deviation (M ± SD).

4.2.1 Participants. We newly recruited participants who play FPS games for at least four hours a week using a computer mouse, right-handed and between the ages of 19 and 50. 24 participants were recruited from a local university. Participants who participated in the LoD perception test were excluded from the TC test. They were compensated 15,000 KRW (≈ 11 USD) each for their participation.

There were 2 women and 22 men (between 19 and 30 years old, 24.12 ± 2.99) who play the FPS game for 7.72 hours a week on average. 5 out of 24 participants knew about LoD, but they have never tuned the LoD settings themselves.

4.2.2 Task and procedure. For the TC task, participants played AIMLABS 'SPIDERSHOT 180 (ULTIMATE)' (Figure 5): two targets appeared one by one in a random position within the current field of view (FoV). The following two targets appeared in a random position 180° behind. This sequence was repeated for one minute. This task forced participants to rotate their FoV 180° per two targets, to maximize the number of observable lifting actions. The mouse sensitivity was set to low (0.69°/mm) but still in the optimal sensitivity range [4].

Participants completed the TC task 12 times: four LoD levels × three sessions per each LoD level. The order of the LoD level was counterbalanced across the participants using a balanced Latin square design [45]. During the TC task, we collected raw USB HID reports from the mouse (Win32 RAWINPUT[5]) and physical mouse movements using a motion capture system (OptiTrack Prime^X 13W, 1.3 MP ±0.30 mm accuracy, 240 FPS, Figure 6).

4.2.3 Result: unintentional movement error. Unintended movement error refers to displacement sensor measurements detected when the mouse is not in contact with the surface, which in theory should not be reported. Specifically, a lifting action was characterized as a segment of motion in which the z position is reported above ≥ 9 mm. The threshold for defining the start and end of a lifting was set at the points when z-position cross 6.5 mm[6] during take-off and landing phases. Upon identifying the lifting chunks, we segmented each lifting into two halves and accumulated the displacement reports generated while its z-position is ≥ 6.5 mm. The errors that occurred in the initial half were labeled *take-off errors*, and the errors in the latter half were labeled *landing errors*.

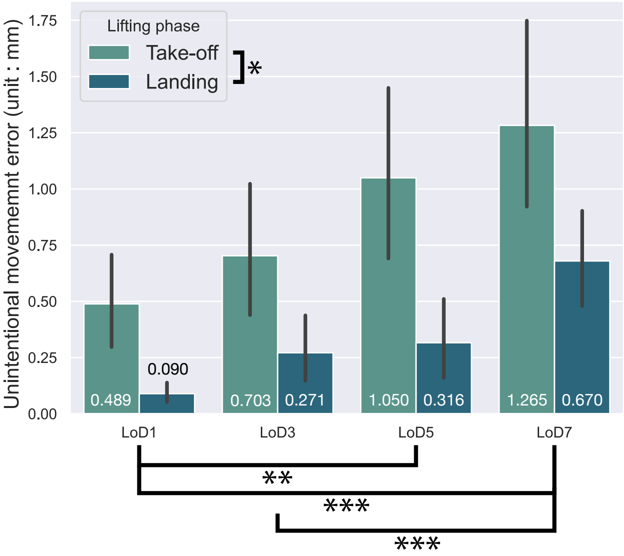

Figure 7: Unintentional movement errors, defined as unintentional sensor reports sent while lifting the mouse, during take-off and landing phases of lifting. A significant main effect of *LoD levels* and the *lifting phase* was found. The error bars are 95% confidence intervals.

For unintentional movement error, a three-way RM-ANOVA was performed with *LoD levels*, *Lifting phase* (take-off and landing), and *Session* as the factors. A significant main effect of *LoD levels* ($F_{2.24,51.48} = 11.812, p < .001, \eta_p^2 = 0.339$) and the *Lifting phase* ($F_{1,23} = 4.29, p = 0.050, \eta_p^2 = 0.157$) was found (Figure 7). There was no significant effect on *Session* ($F_{1.29,29.63} = 1.145, p = 0.309, \eta_p^2 = 0.047$) and interactions between factors. Post hoc analysis revealed that unintentional movement errors escalate as the Lift-off Distance (LoD) levels increase. The LoD1 (0.289 ± 0.289) was significantly lower compared to LoD5 (0.683 ± 1.326, $t = -3.306, p = 0.009$) and LoD7 (0.968 ± 1.454, $t = -5.699, p < .001$). Also the LoD3 (0.487 ± 1.051) was significantly lower compared to LoD7 ($t = -4.035, p < .001$). For *Lifting phase*, the take-off phase (0.876 ± 1.474) exhibited more errors compared to the landing phase (0.337 ± 0.712).

4.2.4 Result: tracking stability. We measured two types of tracking stability: in the spatial domain and in the temporal domain.

The spatial tracking stability was evaluated by measuring spatial jitter in the movement. We first collected HID reports from movements on the mousepad surface: when the z-position is $\leq 6.5mm$ and xy-velocity is $\geq 0.1m/s$ in the motion data. Then a moving average of the raw cursor velocity (from the HID reports, window size=30 units) was obtained as smoothed data, and we calculated the Mean Absolute Error (MAE) between the raw and smoothed cursor velocities as follows: $\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}|v_i - v'_i|$, where N is the number of data points, v_i and v'_i are the raw cursor velocity and the smoothed cursor velocity at the i^{th} data point, respectively.

Figure 8a illustrates the amount of spatial jitters measured at different LoD levels. No significant main effect of *LoD level* ($F_{3,69} = 1.513, p = 0.219, \eta_p^2 = 0.062$), *Session* ($F_{2,46} = 0.662, p = 0.521, \eta_p^2 =$

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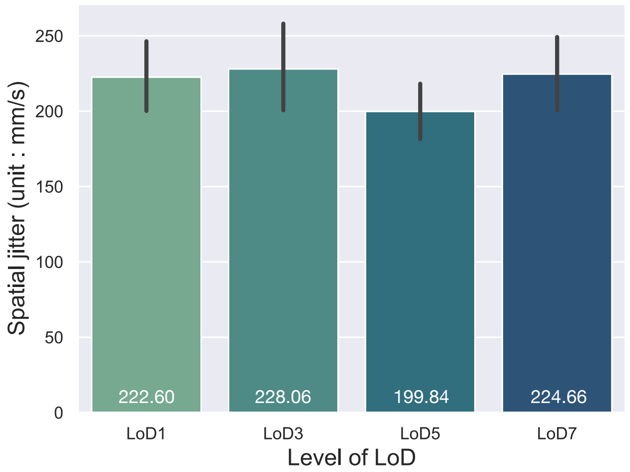
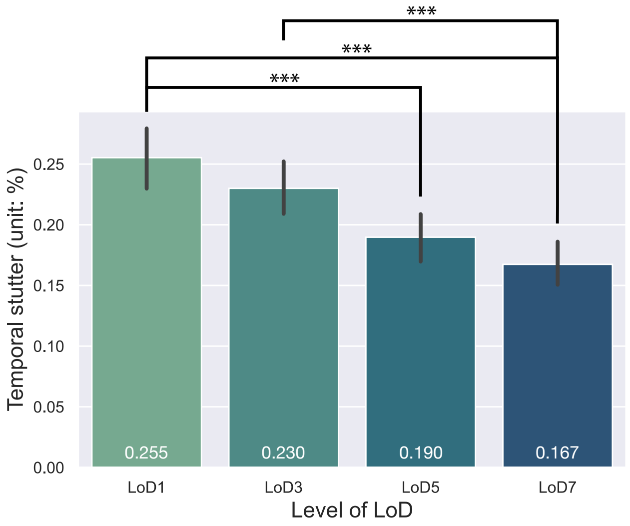
[5] RAWINPUT data contains the raw usb HID reports from the mouse device before the Windows transfer function (i.e., mouse related settings on the control panel) applied.

[6] Note: the mouse pad thickness was 6.0 mm, with an additional margin of +0.5 mm set for the threshold.

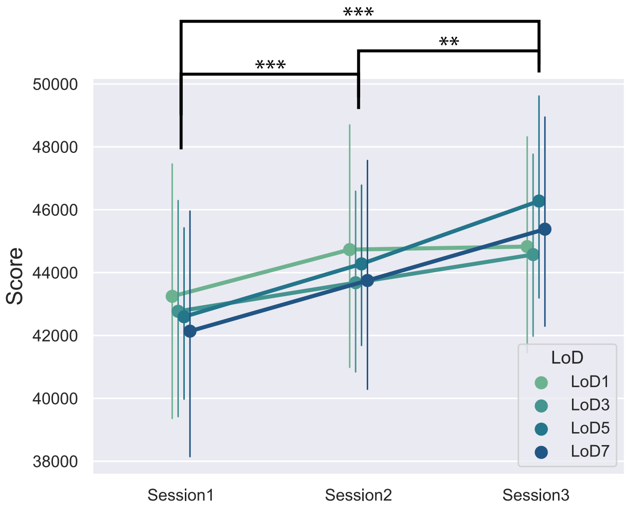


(a) Spatial jitter by LoD levels, defined as a MAE between the raw cursor velocity and smoothed cursor velocity. There is no significant effects of *LoD levels* or *sessions* in spatial jitter.



(b) Temporal stutter by LoD levels, defined as proportion of the counted number of inter-report intervals ≥ 1.5 ms to the total number of HID reports. A significant main effect of *LoD levels* on temporal stutter was found.

Figure 8: The results of two tracking stability measurements: (a) spatial jitter and (b) temporal stutter. The error bars are 95% confidence interval.



	Session1	Session2	Session3
LoD1	43245.92	44732.83	44827.50
LoD3	42768.96	43678.63	44574.42
LoD5	42596.96	44277.17	46277.17
LoD7	42138.00	43748.79	45381.46

Figure 9: The results of AIMLABS SPIDERSHOT 180 (ULTIMATE) scores were divided into sessions and LoD conditions. The score was significantly improved when the *session* repeated, while *LoD* and interactions between factors had no effect on the score. The error bars are 95% confidence intervals.

0.028), and their interactions ($F_{3.41,78.47} = 0.318, p = 0.837, \eta_p^2 = 0.014$) was observed.

As a temporal stability assessment, the stutter of the USB HID report interval was quantified. We collected the HID reports from movements on the mousepad surface: when the z-position is ≤ $6.5mm$ and xy-velocity is ≥ $0.1m/s$ in the motion data. The X17 mouse operates at a polling rate of 1000 Hz and is moving fast enough, the HID reports should always have 1 ms intervals at this speed. If any failed reading (due to low LoD) occurs, the report interval will be 2 ms or larger. We counted the number of inter-report intervals ≥ 1.5 ms and divided that by the total number of HID reports. This proportion quantifies the magnitude of temporal stutter due to missing HID reports.

As shown in Figure 8b, a significant main effect of *LoD levels* on temporal stutter ($F_{3,69} = 13.479, p < .001, \eta_p^2 = 0.370$) was found. The effect of *Session* ($F_{2,46} = 2.327, p = 0.109, \eta_p^2 = 0.092$) and *Interaction* ($F_{6,138} = 0.635, p = 0.702, \eta_p^2 = 0.027$) was not significant. Post hoc analysis showed that temporal stutter was significantly higher in LoD1 (0.255 ± 0.108) compared to LoD5 (0.190 ± 0.081, $t = 4.310, p < .001$) and LoD7 (0.167 ± 0.077, $t = 5.780, p < 0.001$), and LoD3 (0.230 ± 0.093) was significantly higher compared to LoD7 ($t = 4.117, p < .001$).

4.2.5 Result: score. Additionally, we compared the end score of AIMLABS 'SPIDERSHOT 180 (ULTIMATE)' task as a practical performance metric. *Session* exhibited a significant main effect on the score ($F_{2,46} = 32.322, p < .001, \eta_p^2 = 0.584$), where the post hoc test shows that the scores were significantly lower in Session 1 (42687.46 ± 9064.67) compared to Session 2 (44109.35 ± 8298.08, $t = -4.427, p < .001$) and Session 3 (45265.14 ± 8234.55, $t = -8.026, p < .001$). Session 2 scores were significantly lower compared to Session 3 ($t = -3.599, p = 0.002$). No significant main effect was found for *LoD* ($F_{2.21,50.80} = 0.172, p = 0.862, \eta_p^2 = 0.007$) and *LoD* × *Session* interaction ($F_{6,138} = 0.764, p = 0.599, \eta_p^2 = 0.032$).

4.3 Post-experimental survey

In response to the question about their preference for the ideal LoD level, 27 participants favored a lower LoD for better performance, and 15 participants indicated a preference for a higher LoD. The remaining 6 out of the total of 48 respondents mentioned that the optimal LoD setting could differ depending on the circumstances.

The preference for a low LoD was motivated by: "The cursor would shake less when moving my FoV quickly." "It would bounce less in the opposite (movement) direction when LoD was low." and "unintentional cursor movement would decrease."

The preference for a high LoD was motivated by: "When I play FPS games, my body becomes tense, in which case the mouse unintentionally raises off from the pad, and low LoD makes the cursor stutter."

The preference for adjustable LoD was motivated by: "Depending on the games or the users, I think there will be a LoD that suits each individual." and "I think a low LoD was good for lifting and a high LoD for tracking."

5 DISCUSSION

5.1 User perception on LoD changes

Overall, participants could not perceive a difference in LoD until the difference in LoD exceeds 1.20 mm. However, an interesting discovery was found in the comparison of LoD1&LoD3 and LoD5&LoD7 conditions. Even though LoD difference in LoD1&LoD3 condition (0.48 mm) was much smaller than the LoD difference in LoD5&LoD7 condition (1.20 mm), the number of correct responses was notably higher in the LoD1&LoD3 condition. We found that comparing LoD1 (measured LoD = 0.29 mm, virtually zero LoD) against other LoDs is easier than comparing two mid-level LoDs. This observation suggests that the perceptible difference in the LoD difference is nonlinear. This could be further investigated in future work.

5.2 Practical interpretation of error and stability measurements

A higher LoD means a more generous threshold for the displacement sensor, which accepts more movement in the air during the lifting action, resulting in a higher movement error. The possible amount of unintentional movement was approximately up to around 1.2 mm, which corresponds to $\approx 1.08^\circ$–2.16° of the change in FoV in the appropriate sensitivity settings [4]. In pixels, the unintentional error corresponds to ≈26–53 pixels on a full HD screen (1920×1080 px, assuming a narrow FoV of 90° [2]).

In low LoD, the sensor sets a more strict threshold, which accepts displacement readings only if the captured surface image contains dense features or is close to the surface. Under conditions of a low LoD, even a slight deviation from the ideal condition will result in the rejection of the tracking data, consequently resulting in missing USB HID reports and a temporal stutter in the measurements. Given that the mouse has a frequency at 1000 Hz, it is expected to report 1000 data points per second. However, empirical results indicate that stuttering can occur with a probability of up to 0.25 %, resulting in 2 to 3 missing data reports per second.

5.3 Choosing an optimal LoD

In our results, the unintended movement error was LoD1 < LoD5, LoD1 < LoD7, and LoD3 < LoD7 (lower is better, see Figure 7). The tracking stability, measured in terms of temporal stutter, was LoD7 < LoD1, LoD7 < LoD3, and LoD5 < LoD1 (lower is better, see Figure 8b).

Clearly, there is a trade-off between tracking stability and unintentional movement error in lifting action; increasing the LoD enhances temporal tracking stability, but it also leads to greater unintended movement errors. We need to identify a balanced point between stability and error based on the context.

In scenarios that involve significant lifting, it is crucial to prioritize the reduction of accidental movement errors. Simultaneously, the stability provided by higher LoD values should be taken into account. Therefore, LoD3 (0.77 mm) can be considered the optimal condition since it offers a movement error similar to LoD1, but with enhanced stability.

In different situations where most tracking tasks are performed with minimal mouse lifting, LoD5 (1.60 mm) might be seen as the best choice, providing the least spatial jitter. Additionally, temporal stutter remains nearly as minimal as with LoD7, and unintentional movements are somewhat reduced compared to LoD7.

The ideal LoD level may vary based on the task's specifics. Given the balance between unintended movement errors and tracking steadiness, further research is needed to develop a system that offers the most appropriate LoD setting depending on the task type.

5.4 Transition between states in input devices

The unintentional movement error occurred because the transition threshold between the state, for example, between *tracking* or *out-of-range* (see Figure 1), is set differently from the user's intention [5]. This phenomenon is seen not only in mice. Users of the stylus pen experience annoying *hooks* at the end of the stroke due to the delayed transition from the dragging state to the tracking state [21, 32]. Furthermore, the flick gesture [30] with fast finger movement on the touch surface makes the transition from the tracking state to the out-of-range state [42], and the end velocity of the flick gesture, which determines the inertia of scrolling, could be affected by the unintentional movement error [41].

There exists a considerable opportunity to explore how state transition thresholds in various types of input devices affect performance. Therefore, upcoming studies will focus on the consequences of unintentional errors caused by state transitions in different GUI components. Additionally, gaining deeper insights into this domain could help refine input device designs and configurations, enhancing the user experience across a range of applications.

5.5 Limitations

5.5.1 Score metric in TC test. The score metric in the TC test (Section 4.2.5) was an arbitrary measurement provided by AIMLABS. Given that AIMLABS serves as a representative training application for FPS gamers, we hypothesized that the score would exhibit an empirical impact of LoD changes. However, the results did not reveal a statistically significant impact of LoD on the score, indicating that the task might not be suitable to detect the difference. In addition, the score calculation formula in AIMLABS is proprietary and is not available to the public. For future work, a standardized quantitative analysis is required, such as Fitts' Law test [13, 47, 48].

5.5.2 Mouse sensor choice. This research focused exclusively on a single mouse model (EVGA X17) equipped with the Pixart PMW3389 sensor. Although the Pixart PMW3389 is a widely preferred sensor in gaming mice, there are other prominent sensor types on the market, such as the Logitech Hero and Avago ADNS sensors. The EVGA X17 also uses a separate distance sensor to control LoD, which may differ from the SQUAL-based LoD control method. It is important to note that the performance characteristics presented in this study are limited to the device we tested, and the performance of other mice should be independently evaluated. This highlights the need for further research that covers a wider range of devices.

5.5.3 Difference between lifting phases. It was observed that there is a notable difference in the unintentional movement errors between the take-off and landing phases; the take-off phase had a higher error rate than the landing phase. The reasons for this phenomenon have not yet been explored and will be addressed in future research.

6 CONCLUSION

It was believed that increasing LoD within improves tracking stability but increases movement error, but systematic and precise measurement of them has not been carried out. This paper is the first study to quantify the performance of mice with different Lift-off Distance (LoD) settings. Our findings are summarized as follows:

- The proposed mouse LoD measuring jig and method was able to assess the LoD with great accruacy and precision.
- The LoD of four mice was measured and only two (Razer DeathAdder V2 and EVGA X17) actually performed as claimed. The EVGA X17 was chosen as it had the best range and granularity in the LoD setting.
- A psychophysical experiment reveled that the human perception threshold of LoD setting was about 1.2 mm.
- The unintentional cursor movement error was pronounced in the take-off phase of the lifting. As the LoD increased, the average amount of error increased to approximately 1.2 mm.
- Tracking stability decreased as LoD increased. The mouse experienced more skipped sensor reports in low LoD which resulted in a temporal instability. However, spatial stability was not significantly affected.

We believe that this study could provide valuable information for both hardware manufacturers and gamers. This work could contribute to the development of a more standardized approach to evaluating mouse LoD performance. Future research could focus on exploring different mouse models and sensors to validate and expand these findings.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (RS-2023-00211872 and RS-2023-00223062).

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