



Higher refresh rate does not necessarily improve scrolling experience on mobile phones

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ABSTRACT

The present study explored how different refresh rates affect the scrolling experience on mobile phones. Users ($N = 76$) completed two out of three scrolling tasks involving texts and/or images, with refresh rate set at 60, 90, or 120 Hz. Users were required to rate the perceived smoothness and levels of jittering at each refresh rate and detect if there was a perceivable change in refresh rates while scrolling. The results showed that refresh rates of 90 and 120 Hz enhanced perceived smoothness and reduced screen jittering compared to 60 Hz, with minimal differences observed between 90 and 120 Hz across most tasks. Moreover, users showed greater sensitivity to changes in refresh rate between 60 Hz and higher values than to changes within the 90 Hz to 120 Hz range, with this difference being more pronounced when the refresh rate decreased. Additionally, users displayed a more conservative response bias toward refresh rate decreases compared to increases in the specific scrolling task. These findings shed light on users' perceptual experience of scrolling with various refresh rates, and offer useful design guidelines for optimising the screen display of mobile devices.

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1. Introduction

According to the smartphone usage statistics reported by Backlinko Team, as of 13 March 2024, the number of smartphone users worldwide has reached approximately 4.88 billion and is projected to reach 6 billion by 2027 (Backlinko Team 2024). Reports showed that in 2023, Chinese users spent about 3.72 h per day on their smartphones, while users from the United States took about 4.34 h per day on smartphones. Common uses for smartphones include information searching, browsing, and entertainment, all of which heavily rely on the display's refresh rate to provide users with an optimal experience (Hogan 2014).

The refresh rate, measured in Hertz (Hz), refers to the frequency at which a device redraws the entire visible display per second, as noted by You, Nam, and Lee (2020). A higher refresh rate, such as 120 Hz, is capable of displaying more frames compared to a 60 Hz screen, thereby reducing the difference between two adjacent frames' images (LeClair 2022). It is worth noting that the terms 'refresh rate' and 'frame rate' are sometimes used interchangeably, though the latter is measured in frames per second (FPS).

Generally, a higher graphics card frame rate results in more frequent image refreshes on the monitor each second. The increased number of image refreshes should lead to less motion blur and provide smoother animation and object movement on the screen.

Previous studies have investigated the impact of refresh rate or FPS on user experience for various tasks, such as target searching/clicking, video watching, webpage browsing, and game playing (Agboma and Liotta 2006; Claypool and Claypool 2007; 2009; Egilmez et al. 2017; Spjut et al. 2019). These studies consistently show that increasing the refresh rate leads to improved task performance and higher subjective ratings. For example, in a shooting game that evaluated tracking and hitting skills, target tracking completion time decreased with higher refresh rates (Spjut et al. 2019). Additionally, Claypool and Claypool (2007) reported that higher refresh rates were associated with improved game performance, such as shorter movement times and more remaining health points, as well as higher user ratings for display quality and game playability. Further, Janzen and Teather (2014) found that the number of targets clicked while moving was significantly

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higher at a baseline level of 60 FPS than at 30 and 15 FPS but similar to that at 45 FPS. These results suggest a close relation between screen refresh rate and user experience, and that the greater the range between refresh rates, the more it can cause differences in user evaluations and performances.

The relation between refresh rate and perceived quality is context-dependent (Agboma and Liotta 2006; Gulliver and Ghinea 2004; see a review by Chen and Thropp 2007). For instance, Gulliver and Ghinea (2004) found that videos with different themes displayed on a computer had varying levels of subjective satisfaction at high FPS (i.e. 25 FPS), with pop video clips having higher subjective ratings on the perceived quality and enjoyment compared to other themes like weather, news, and choir. Similarly, Agboma and Liotta (2006) evaluated video quality on mobile phones and larger screens, where participants watched video clips from different categories to determine the lowest FPS that could satisfy them. Researchers found that participants preferred a high FPS for specific videos, such as football, cricket, video games, and music concerts. This preference may be due to the increased likelihood of losing visual details, experiencing stuttering and facing audio-visual synchronisation issues when fewer frames were refreshed per second (e.g. below 10 FPS) for high-motion videos, which becomes more noticeable on large screens (Agboma and Liotta 2006).

Building on these findings, it is crucial to explore how refresh rate affects primary touchscreen interactions on smartphones. Scrolling is a basic, application-independent touchscreen interaction frequently performed in everyday life (Ciman, Wac, and Gaggi 2015), constituting more than 30% of overall mobile usage and nearly 60% of browser-related activities (Yu et al. 2015). The continuous and dynamic nature of scrolling makes refresh rate a critical factor, however, only a limited number of studies have investigated the scrolling experience across different refresh rates on smartphones (e.g. Egilmez et al. 2017; Han et al. 2013). Egilmez et al. (2017) conducted a study to investigate the impact of refresh rates (20, 30, 45, 60 FPS) on scrolling experience during mobile web page navigation. The study revealed that higher refresh rates were associated with increased subjective satisfaction scores when web browsing. Similarly, Han et al. (2013) reported improved user satisfaction as the refresh rate increased from 5 to 60FPS while scrolling through news. However, these studies did not examine refresh rates at higher levels.

Recently, high refresh rate displays such as 90 and 120 Hz have become more prevalent in smartphones (LeClair 2022). However, enabling a higher refresh rate not only requires more powerful hardware but also

results in a shorter standby time. For example, it has been reported that battery drains at least 20% faster for a 120 Hz refresh rate compared to a 60 Hz refresh rate (Frumusanu 2020). To balance power conserve and provide a smooth interaction experience, many flagship phones (such as the iPhone 14 Pro/ProMax and the Samsung Galaxy S22 Ultra) have developed an adaptive or variable refresh rate strategy. Studies on adaptive refresh rate systems are relatively few (Egilmez et al. 2017; Han et al. 2013), primarily focusing on developing models that dynamically adjust the refresh rate of mobile phone displays, typically up to 60 FPS. To our knowledge, no prior research has explored the user experience of scrolling on a mobile phone with refresh rates higher than 60 FPS, with little attention given to how users respond to dynamic changes in high refresh rates.

Existing studies on higher refresh rate experiences have mainly been conducted on computer screen, indicating a marginal improvement in perceived quality when the refresh rate exceeds a certain threshold (Denes et al. 2020; Han et al. 2021). For example, one such study by Denes et al. (2020) used various moving stimuli and found that visual sharpness and motion smoothness increased significantly with refresh rate, but the increase slowed down when the refresh rate went above 100 Hz. Likewise, Han et al. (2021) reported increased steady-state motion visual evoked potentials as the screen refresh rate changed from 60 Hz to 120 Hz, but the trend began to slow down beyond 120 Hz. Accordingly, the subjective perception of a screen's quality does not increase linearly with the refresh rate, but rather appears to follow a logarithmic function. Nevertheless, these studies primarily relied on traditional visual perception experiments using stimuli such as checkered circles, which do not fully capture the diversity of scrolling content commonly experienced on a smartphone.

To sum up, previous studies have shown that higher refresh rates are associated with improved user experience and better performance in a variety of tasks (e.g. Chen and Thropp 2007; Egilmez et al. 2017; Janzen and Teather 2014; You, Nam, and Lee 2020), with diminishing returns beyond a certain threshold (Denes et al. 2020; Han et al. 2021). However, research on refresh rates and user experience with mobile devices, particularly in the context of scrolling interactions and adaptive refresh rate systems, is limited (Egilmez et al. 2017; Han et al. 2013). Notably, studies on refresh rates exceeding 60 Hz for mobile phone are absent. As a result, while refresh rates of 90 Hz or 120 Hz displays are now prevalent in many flagship phones, it remains unexplored whether these very high refresh rates, which consume significantly more energy, actually provide improved

scrolling experiences during everyday mobile activities, compared to the standard 60 Hz. Moreover, there is limited understanding of user sensitivity to refresh rates varying dynamically between standard and higher levels.

To address this gap, the present study aimed to investigate how the refresh rate affects the user experience during daily scrolling tasks on smartphones. The importance and prevalence of scrolling operations on mobile devices have been discussed earlier. We manipulated the refresh rate at 60, 90, and 120 Hz across different scrolling tasks, including scrolling through texts and/or images, which were carefully chosen to reflect diverse, daily-life scenarios commonly encountered during mobile device use. For example, text-only scrolling was designed to represent text-heavy scenarios, such as reading articles or documents. Text + image scrolling was designed to represent mixed-media scenarios, such as browsing social media pages or e-commerce platforms that combine textual and image elements. Fullscreen image scrolling was designed to represent tasks focused exclusively on image-based content, such as viewing photo albums or image galleries. These task types were selected to cover a broad range of common user activities on a mobile phone. Users were required to rate the perceived smoothness and levels of jittering at each refresh rate, as well as detect if there was a noticeable change in refresh rates through dynamic adjustments. By focusing on real-world scrolling tasks and extending the investigation to refresh rates higher than 60 Hz, the present study is expected to provide a valuable reference for developing efficient display refresh strategies for mobile devices that balance user experience and energy consumption.

2. Method

2.1. Design

To explore how refresh rate affects the user experience during daily smartphone scrolling, the present study employed two tasks: an evaluation task and a change detection task. The evaluation task aimed to investigate the impact of different refresh rates, typically set by default on smartphones, on smoothness perception across various scrolling scenarios including scrolling through text-only pages, image-only content, and a combination of text and images. This task took about 15 min to complete. The change detection task was designed to explore the conditions under which refresh rate adjustments may become noticeable to users. If users can detect these changes, especially when the refresh rate decreases, it could negatively affect the scrolling experience. Therefore, the inclusion of the

detection task informs the efficient implementation of adaptive refresh rates to ensure smooth performance while optimising energy consumption. The detection task took about 35 min to complete.

In the evaluation task, display refresh rate (60, 90, 120 Hz) served as the main independent variable, with subjective evaluations of perceived smoothness and perceived screen jittering as the key dependent variables. In the change detection task, initial refresh rate (60, 90, 120 Hz) and trial condition (increase, decrease, no-change) were the independent variables. The dependent variable was change detection sensitivity (d'), which measures how well one can discriminate between refresh rate changes from the no-change condition. A higher value of d' indicates better sensitivity or discrimination ability. Additionally, response bias (β) was computed, referring to one's tendency to respond in a particular way (e.g. 'yes' or 'no') during the change detection task. Larger β values indicate a higher tendency to say 'no', reflecting a more conservative response style. According to previous studies on refresh rate, user experience and task performance (e.g. Chen et al. 2007; Denes et al. 2020; Egilmez et al. 2017), we hypothesised that users' scrolling experience would improve with higher refresh rates, but that the rate of improvement would slow down as the refresh rate continues to increase beyond a certain level. We also hypothesised that larger differences in refresh rate would be more noticeable compared to smaller adjustments.

2.2. Users

A total of 76 users (31 males; aged 20–44 years) took part in the study. They were selected randomly from the general population aged between 18 and 45 years old, through both online and verbal communication. Users were randomly assigned to complete two of the three scrolling tasks to prevent fatigue, resulting in 51 users in the text-only scrolling task, 47 users in the text + image scrolling task, and 45 users in the fullscreen image scrolling task. A statistical power analysis (Faul et al. 2007) indicated that a minimum sample size of $N = 43$ was sufficient to detect a medium effect size ($f = 0.25$), with $\alpha = 0.05$ and power = 0.95 for each task. All users reported having normal or corrected-to-normal vision and having experience in using touchscreen mobile phones. Detailed demographic information is provided in Appendix 1.

In summary, our sample included users of different genders, ages, mobile operating system experiences (iOS and Android), years of mobile phone use, and various daily mobile usage duration. Moreover, users' sensitivity to display or operation fluency was assessed

before the experiment, with sensitive users accounting for 78.43% to 85.11% of the total sample in each scrolling task. The diversity in demographics and mobile usage patterns enhances the representativeness of the sample. No significant differences were found in the tested demographic variables among users across the three scrolling tasks (all $p > .290$). The study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences. All users provided written informed consent prior to the study and received a cash reward of ¥50 (approximately \$7) upon completion of the study.

2.3. Apparatus, materials, and procedure

Users were instructed to perform a scrolling task and rate their subjective experience (Appendix 2) on an OPPO Find X3 mobile phone with a 6.7-inch AMOLED screen (Active Matrix Organic Light Emitting Diode; 3216×1440 resolution), running the Android 12.0 operating system with a 240 Hz touch sampling rate, in portrait orientation and light mode. The brightness of the phone screen was kept consistent (auto-brightness was off) throughout the experiment to control for potential confounding effects on users' perception of display quality. The task utilised mock user interfaces (UIs) designed to feature three different types of content: text-only, image-only, and text + image combinations (as shown in Figure 1(A)). Specifically, the text-only interface was designed to resemble online news articles or e-books. In addition, a fullscreen image interface was designed to include solely images resembling photo gallery or album. We also designed a text + image interface to replicate the layout commonly seen on e-commerce platforms. In the text-only and text + image scrolling tasks, vertical scrolling navigation was required. Users moved their finger up and down on the screen, causing the content to scroll in the same direction, incorporated with inertial movement. In contrast, for the image-only scrolling task users had to move their finger horizontally through a sequence of full-screen images. It is worth noting that all interfaces were designed with sufficient content length to ensure continuous scrolling: 10 pages for the text-only and text + image tasks, as well as 20 images for the full-screen image-only scrolling task. To maintain a seamless experience, no progressive loading was applied.

In each scrolling task, users were provided with a practice session, during which the refresh rate was systematically varied between 60, 90, and 120 Hz, in ascending and descending orders across trials of 20-second scrolling each. It is important to note that the screen refresh rate was carefully manipulated throughout the experiment. Initially, the screen refresh rate of

the mobile phone used for the study was set to an 'Auto selection' mode, allowing for the implementation of various refresh rate conditions up to 120 Hz. Then, the target refresh rate during scrolling was regulated by Android Display. Mode classes based on the current experimental condition. The target refresh rate was validated prior to the test by comparing it with a specific developer option indicating the current refresh rate of the display. Users were informed of the refresh rate during each practice trial by displaying it at the top of the screen, in order to establish the relationship between different refresh rates and user experience. The practice session was repeated until users confirmed that they had fully understood how to perform the task.

The critical experiment comprised two sections for each scrolling task. The first section was an evaluation task where the refresh rates changed randomly across scrolling trials, each lasting 20 s. After each trial, their perception of scrolling smoothness was recorded on a 5-point Likert scale ranging from 1 (*not at all smooth*) to 5 (*extremely smooth*), similar to a MOS rating scale with 1 being the worst quality and 5 being the best. Additionally, users had to rate their perceived screen jittering/flickering on a 7-point Likert scale of 1 (*not at all jittery*) to 7 (*extremely jittery*). Users were tested three times on each refresh rate for every scrolling task.

The other section was a change detection task, in which the refresh rate could change within a 40-second trial of scrolling. Specifically, the refresh rate in the last 20 s of a trial may increase (i.e. 60–90 Hz, 60–120 Hz, 90–120 Hz) or decrease (i.e. 90–60 Hz, 120–60 Hz, 120–90 Hz), or remain unchanged (i.e. 60–60 Hz, 90–90 Hz, 120–120 Hz), resulting in nine specific trial conditions. The no-change conditions served as baseline measures. The nine trial conditions were presented in a randomised order and repeated three times each, resulting in a total of 27 trials for each scrolling task. After completing each trial, users were asked to indicate whether or not they noticed a change in the refresh rate while scrolling (*yes/no*; see surveys in Appendix 2).

Users always performed the evaluation task section followed by the change detection task section for each scrolling task. During the critical experimental trials in both task sections, the refresh rate being tested was not displayed on the screen, keeping users unaware of the refresh rate setting in use. Users were instructed to scroll continuously until the end of the trial, at fast, slow, and preferred pace during each trial. Breaks were allowed between sections. The entire experiment took about 50 min to complete. The experimenter stayed with the user in the test room throughout the entire experiment session to ensure continuous scrolling and to minimise any procedural inconsistency. By

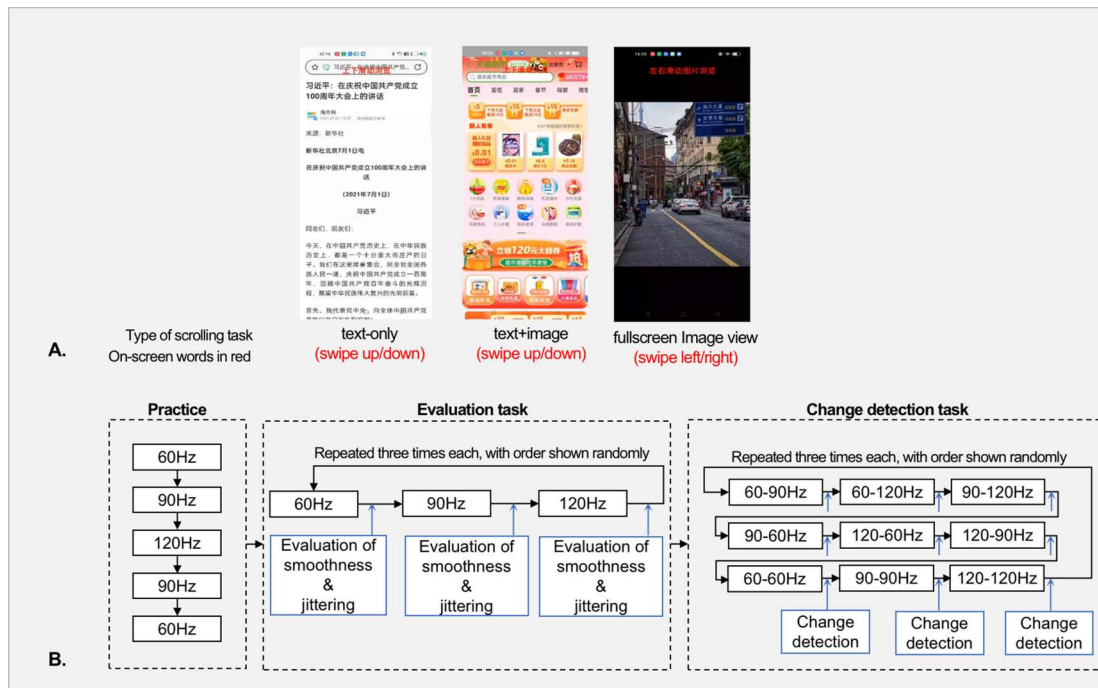


Figure 1. Types of scrolling tasks (A) and diagram of study procedures for each task (B).

doing so, we ensured that users were exposed to various refresh rates being tested. In other words, the refresh rate was a primary factor influencing user experience in the present study. Experimental procedures are illustrated in Figure 1(B).

3. Result

3.1. Data analyses

In the following sections, data of different scrolling tasks were analyzed separately using R version 4.2.2 (R Core Team 2022). For the evaluation task, we conducted ANOVAs for both smoothness and jittering rating scores despite violations of normality (all $p < 0.05$ in the Jarque–Bera normality test using *moments* Package in R; Jarque and Bera 1980; Komsta and Novomestky 2015). ANOVA and F-statistics are known to be robust against violations of this assumption, while alternative solutions, such as data transformation for non-normally distributed data and non-parametric procedures, can lead to difficulties in data interpretation and potential loss of information (Blanca et al. 2017; Khan and Rayner 2003; Norman 2010).

3.2. Perceived smoothness scores in the evaluation task

In every scrolling task, the smoothness rating scores for each refresh rate were compared using a one-way repeated measures ANOVA, with refresh rate (60, 90,

120 Hz) as the within-subject factor. The mean scores of perceived smoothness for each condition are displayed in Figure 2 and Appendix 3. The statistical results from the ANOVAs are summarised in a table in Appendix 4. We found a significant main effect of refresh rate on the scores of perceived smoothness in every scrolling task: text-only ($F(2, 100) = 39.95, p < .001, \eta_p^2 = 0.44$), fullscreen image view ($F(2, 88) = 26.81, p < .001, \eta_p^2 = 0.38$), text + image ($F(2, 92) = 28.01, p < .001, \eta_p^2 = 0.38$). Post hoc pairwise comparisons using Bonferroni correction (and thereafter) indicated significant differences in the rating scores of perceived smoothness between refresh rates of 60 Hz and 90 Hz, and between 60 Hz and 120 Hz, across all scrolling tasks (all $p < .001$). The score of perceived smoothness was significantly lower when scrolling with a refresh rate of 60 Hz compared to 90 Hz or 120 Hz. Moreover, the smoothness score for 90 Hz was significantly lower than that for 120 Hz when scrolling vertically through interleaved texts and images (i.e. text + image scrolling task; $p = .006$). However, the score was not significantly different between 90 and 120 Hz for two other tasks (all $p > .100$).

3.3. Perceived jittering scores in the evaluation task

In every scrolling task, a one-way repeated measures ANOVA was also conducted on the mean screen jittering scores to compare different conditions, with the within-subject factor being refresh rate (60, 90,

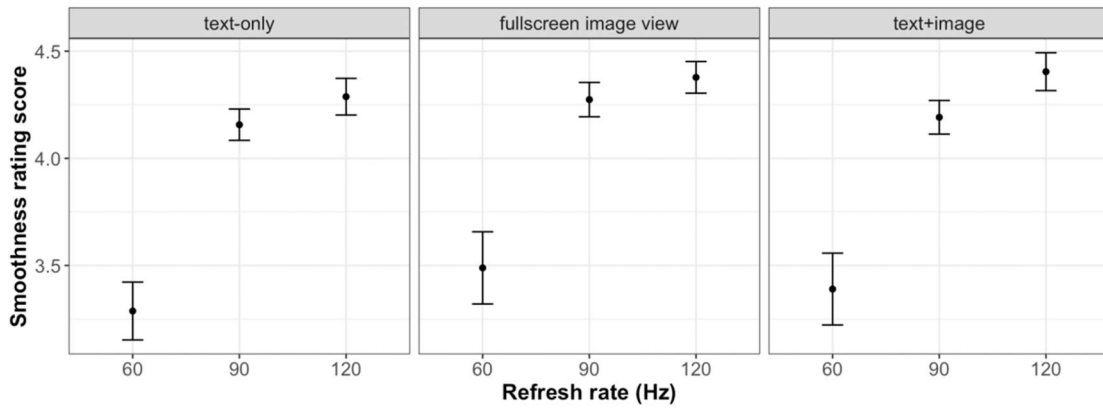


Figure 2. Mean perceived smoothness scores for the three refresh rates in the three types of scrolling task (shown in different facets). Error bars indicate standard error of the mean.

120 Hz). The mean scores of perceived screen jittering for each condition are displayed in Figure 3 and Appendix 3. The statistical results from the ANOVAs are summarised in a table in Appendix 4. The main effect of refresh rate on the level of perceived jittering was statistically significant in every scrolling task: text-only ($F(2, 100) = 31.49, p < .001, \eta_p^2 = 0.39$), fullscreen image view ($F(2, 88) = 30.68, p < .001, \eta_p^2 = 0.41$), text + image ($F(2, 92) = 21.51, p < .001, \eta_p^2 = 0.32$). Post hoc analyses consistently showed that more jitters were perceived for a refresh rate of 60 Hz compared to 90 Hz or 120 Hz (all $p < .001$), regardless of the types of scrolling tasks. However, the scores were not significantly different between the refresh rate of 90 and 120 Hz for each scrolling task (all $p > 0.100$).

3.4. Change detection performance

Change detection sensitivity (d') was computed by comparing the hit rate in the increase (60–90 Hz, 90–120 Hz, 60–120 Hz) or decrease (90–60 Hz, 120–90 Hz, 120–60 Hz) trial conditions to the relative false alarm

rate in the no-change trial conditions (60–60 Hz, 90–90 Hz, 120–120 Hz), following z-transformation (Figure 4). Note, before applying the z-transformation, both the hit rate and false alarm rate were adjusted in compliance with the recommendations by Hautus (1995). Three separate two-way ANOVAs with repeated measurements were conducted on d' values for each scrolling task. The two factors examined were change direction (increase or decrease) and change interval (60 & 90 Hz, 90 & 120 Hz, 60 & 120 Hz). Detailed statistical results are shown in Appendix 5.

In sum, we found that users exhibited heightened sensitivity to conditions where the refresh rates varied between 60 Hz and higher values compared to conditions where the refresh rates changed within the interval of 90 and 120 Hz. This is indicated by a significant main effect of change interval: text-only ($F(2, 100) = 16.90, p < .001, \eta_p^2 = 0.25$), fullscreen images view ($F(2, 88) = 6.12, p = .003, \eta_p^2 = 0.12$), and text + image ($F(2, 92) = 20.22, p < .001, \eta_p^2 = 0.31$). Post hoc tests indicated higher d' values for the change interval of 60 & 90 Hz and 60 & 120 Hz compared to the interval of 90 &

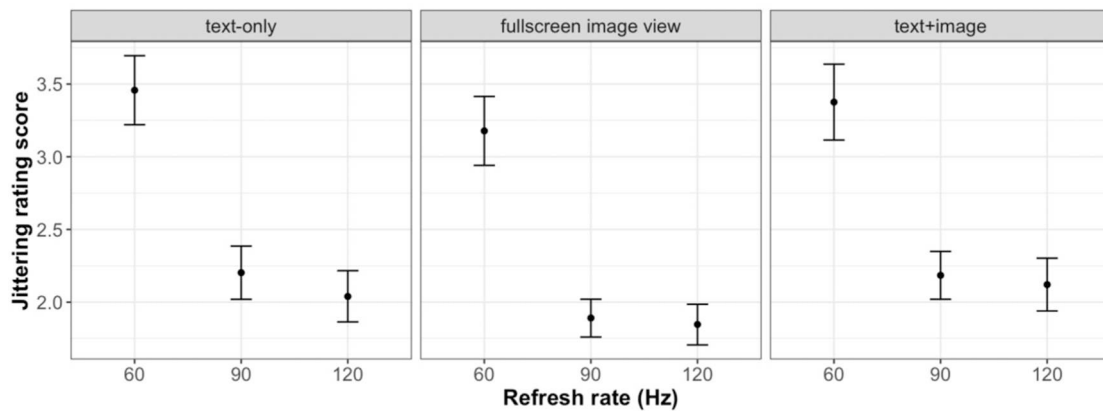


Figure 3. Mean perceived jittering scores for the three refresh rates in the three types of scrolling task (shown in different facets). Error bars indicate standard error of the mean.

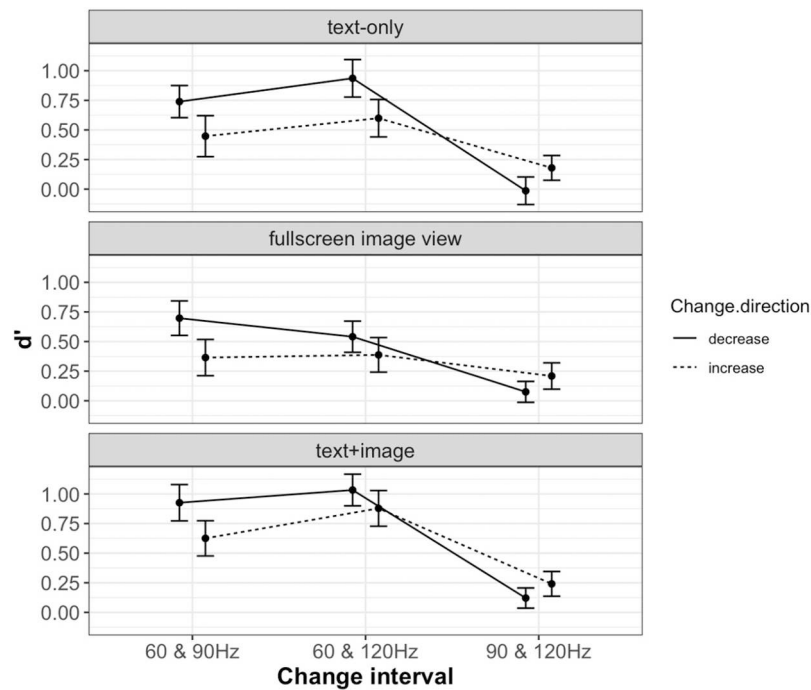


Figure 4. Mean response sensitivity (d') for different trial conditions and across the three scrolling tasks. Error bars indicate standard error of the mean.

120 Hz (all $p < .050$). However, there was no significant difference in d' values between the interval of 60 & 120 Hz and 60 & 90 Hz (all $p > 0.100$). The main effect of change direction was not significant for every task (all $p > 0.100$).

Furthermore, we observed a significant interaction between change direction and change interval in the text-only scrolling task ($F(2, 100) = 4.75, p = .011, \eta_p^2 = 0.09$), and marginally significant interactions in the fullscreen image scrolling task ($F(2, 88) = 2.44, p = .093, \eta_p^2 = 0.05$), and text + image scrolling task ($F(2, 92) = 2.57, p = .082, \eta_p^2 = 0.05$). These results suggest that the effect of change intervals differs between change directions. Post hoc tests for all tasks revealed that decreasing to 60 Hz from either refresh rates resulted in higher d' values compared to decreasing to 90 Hz from 120 Hz (all $p < .050$). Nevertheless, there were no significant difference across change intervals with increased refresh rates (all $p > .010$), with an exception that, in the text + image scrolling task, higher d' values were observed for an increase from 60 Hz to 120 Hz compared to an increase from 90 Hz to 120 Hz ($p = .005$). Further analyses for all tasks revealed that d' values were higher when refresh rates decreased from 90 Hz to 60 Hz compared to when they increased from 90 Hz to 120 Hz (all $p < .050$).

The study also computed the response bias (β) for different conditions (Figure 5). Three separate two-way ANOVAs with repeated measurements were conducted on β values for each scrolling task. The two factors were

change direction (increase, decrease) and change interval (60 & 90 Hz, 90 & 120 Hz, 60 & 120 Hz). Detailed statistical results are shown in Appendix 6.

In sum, we observed no significant main effects or interactions for the text-only scrolling task and the text + image scrolling task (all $p > .100$). However, for the fullscreen image scrolling task, users displayed a more conservative response bias for refresh rate decreases than increases. This is indicated by a significant main effect of change direction ($F(1, 44) = 6.36, p = .015, \eta_p^2 = 0.13$). On average, higher β value was associated with a decrease in the refresh rate compared to refresh rate increases. In addition, change direction significantly interacted with change interval for the fullscreen image scrolling task ($F(2, 88) = 4.36, p = .016, \eta_p^2 = 0.09$). However, post hoc analyses indicate no statistically significant differences between every pair of conditions (all $p > .050$).

4. Discussion

Consistent with previous studies (e.g. Agboma and Liotta 2006; Claypool and Claypool 2007; 2009; Egilmez et al. 2017; Han et al. 2013; 2021; You, Nam, and Lee 2020) and in line with our first hypothesis, we found that higher refresh rates improved perceived smoothness and reduced screen jittering. However, the benefits of further increasing the refresh rate were limited in most scrolling tasks. Moreover, users exhibited

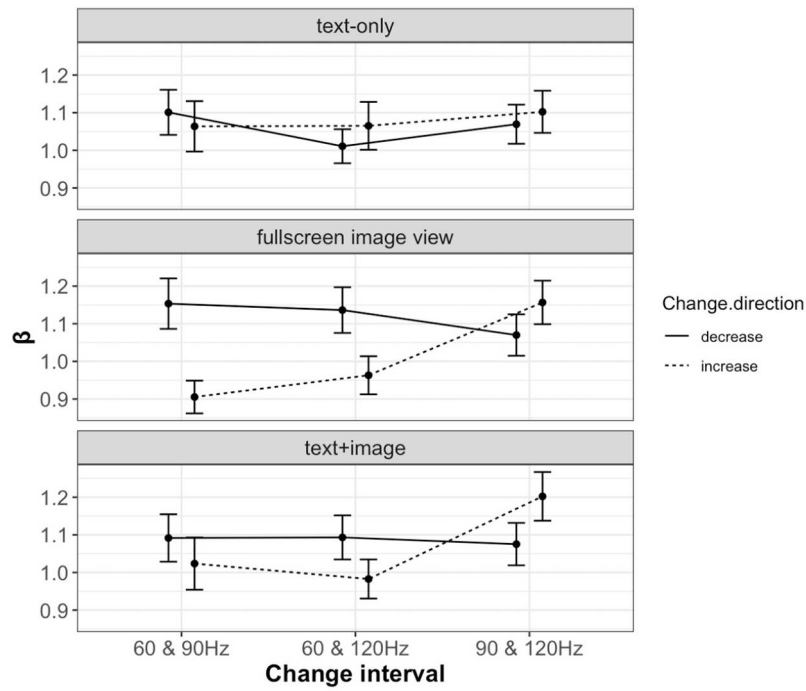


Figure 5. Mean response bias (β) for different trial conditions and across the three scrolling tasks. Error bars indicate standard error of the mean.

heightened sensitivity to changes in refresh rates between 60 Hz and higher values compared to changes within the 90 Hz to 120 Hz range. This finding generally aligns with our second hypothesis, which suggests that large changes in refresh rate can be more noticeable. Notably, users showed greater sensitivity to changes between 60 and 90 Hz than between 90 and 120 Hz, despite the identical magnitude of change. Further, we noted that users tended to exhibit a more conservative response bias for refresh rate decreases compared to increases in the specific scrolling task.

4.1. User experience across three refresh rates

The finding that scrolling experience was better with the refresh rate of 90 and 120 Hz, compared to 60 Hz, is supported by previous research showing reduced motion blurs and increased subjective ratings when more frames are shown per second on a typical PC display (e.g. Agboma and Liotta 2006; Claypool and Claypool 2007; 2009; Han et al. 2021; You, Nam, and Lee 2020) and mobile phones (e.g. Egilmez et al. 2017; Han et al. 2013). The human visual system allows for persistence of vision, which means that retinal impressions continue to activate the visual system even after the visual stimulus has ended, resulting in visual afterimages (Leguire and Blake 1982; Virsu and Laurinen 1977). This phenomenon allows for a rapid series of images to create an illusion of motion, which

is the foundation of animation and cinema. Additionally, cognitive processes are also involved, as humans tend to perceive the successive presentation of static visual stimuli as continuous motion without motion smear (Burr 1980; Kintz and Witzel 1972). Thus, displaying more frames per second allows for rapid processing of consecutive static images with minor differences, resulting in a seamless animation and a smooth scrolling experience on the mobile phone interface.

However, the benefit of higher refresh rates was limited when beyond a certain threshold. In the present study, we observed a substantial improvement in the users' subjective experience as the refresh rate increased from 60 Hz to 90 Hz, with a further marginal improvement observed beyond 90 Hz for two out of three scrolling tasks. This is in line with those who had noted a non-linear relationship between refresh rate and subjective experience (e.g. Egilmez et al. 2017; Janzen and Teather 2014; Nasiri et al. 2015). Therefore, we suggest that for a smartphone display, both 90 and 120 Hz perform equally well for most scrolling tasks and scenarios, such as browsing text-only pages or scrolling through fullscreen images. However, in the case of vertically scrolling over pages with interleaved texts and images (i.e. text + image scrolling task), we found that a higher refresh rate of 120 Hz provided a smoother scrolling experience compared to 90 Hz.

It is possible that the size of objects displayed on the smartphone screen could have an impact on the users'

scrolling experience. The images utilised in the present study were considerably larger in size than the font size of the texts, potentially leading users to perceive screen flickering more prominently when scrolling through content that had images, compared to text-only browsing. This finding can be explained by Barten's model of human eye contrast sensitivity, which emphasises that perceptibility and contrast sensitivity are influenced by the size of objects within the visual field (Barten 2003). Moreover, larger objects are typically associated with greater sensitivity and can result in more flicker-related issues on the screen than smaller objects (You, Nam, and Lee 2020). While the field size of objects is generally an important factor influencing scrolling experience, there was an exception. Specifically, when users swiped horizontally to view fullscreen images, there was no significant difference in the smoothness scores between the refresh rates of 90 and 120 Hz, despite the large field size of fullscreen images.

We speculate that scrolling speed may also play a role in influencing the user scrolling experience. Although users were instructed to swipe continuously from right to left or left to right to view the next or previous images in the fullscreen image scrolling task, as they would with a book, many users did not perform another swipe until the onset of a different image, resulting in relatively slow scrolling speeds. The slow scrolling speed might have contributed to a reduced ability to discern differences between refresh rates of 90 and 120 Hz, even with the presence of large images on the screen. This speculation is consistent with previous studies highlighting the importance of taking scrolling speed into account when determining the optimal refresh rate for user satisfaction (Han et al. 2013). Consequently, we recommend employing a higher refresh rate (e.g. 120 Hz) when users engage in fast scrolling through pages containing large objects on mobile phones.

4.2. Change detection sensitivity

When varying the refresh rates within a trial, we found that users exhibited a greater level of sensitivity to changes between 60 and 90 Hz, as well as between 60 and 120 Hz, compared to changes between 90 and 120 Hz. This effect was particularly pronounced when the refresh rate decreased, whereas no such effect was observed when the refresh rate increased. It is not surprising that a substantial shift in refresh rate (from 120 Hz to 60 Hz) was linked to a greater likelihood of detecting a difference, compared to a small refresh rate adjustment (from 90 Hz to 60 Hz). Earlier studies have suggested that as the disparity between refresh rate levels increases, differences in user evaluations and

performance become more prominent (Egilmez et al. 2017; Janzen and Teather 2014). An important finding is that in every scrolling task, users exhibited greater sensitivity for the refresh rate decreasing from 90 Hz to 60 Hz, as opposed to when it varied from 120 Hz to 90 Hz. This further supports an increase in the Just Noticeable Difference (JND) as the starting refresh rate gets higher (DoVale, 2017). That is, detecting changes in refreshing rate requires a more substantial change in the refresh rate for a high initial frequency than a relatively lower initial frequency. This finding also highlights the limitations of the human visual system in detecting differences in stimuli that refresh at very high frequencies (Denes et al. 2020; Han et al. 2021). However, this account cannot explain the heightened sensitivity when the refresh rate decreased from 90 Hz to 60 Hz, compared to when it increased from 90 Hz to 120 Hz, with both conditions sharing the same initial refresh rate. Therefore, an alternative explanation could be that users were more sensitive to refresh rate changes that resulted in poorer subjective experience.

We did not find any significant differences in sensitivity between conditions where refresh rates increased from 60 Hz to 120 Hz and those increasing from 90 Hz to 120 Hz, with one exception. In the text + image scrolling task, increasing from 60 Hz to 120 Hz was associated with a higher level of sensitivity compared to when it increased from 90 Hz to 120 Hz. Previous research has suggested that the attractiveness of visual content can modulate attention allocation, leading to enhanced cognitive processing and change detection sensitivity (Chen, Liu, and Nakabayashi 2012; Righi et al. 2017). We speculate that the text + image scrolling task, which simulated the complex e-commerce shopping interface of Alibaba, may have captured more attention from users compared to other tasks, thereby increasing their sensitivity to detecting refresh rates changing in a dramatic and substantial way. Then, we recommend avoiding dramatic changes in refresh rate in the daily-life applications, particularly when scrolling through pages that contain interleaved texts and images.

4.3. Response bias

Interestingly, despite being sensitive to decreases in refresh rate and the resulting reduced user experience, users did not always show a willingness to provide feedback on such decreases. In the fullscreen image scrolling task, we observed a trend where users tended to give more conservative responses, frequently reporting 'no change', when the refresh rate decreased compared to when it increased, although they displayed heightened sensitivity to refresh rate decreases. This trend may be

attributed to poorer user experience and possibly the activation of negative emotions associated with the reduction in refresh rate. Supporting evidence for this can be found in Yuen and Lee (2003), who reported that negative emotions can activate negative evaluations of risk choices and encourage conservative responses when facing choice dilemmas. Our findings emphasise the importance for phone manufacturers to effectively monitor refresh rate changes and gather feedback to ensure an optimal user experience.

4.4. Recommendations

In summary, the following recommendations are proposed for display refresh strategies in mobile devices:

First, a refresh rate of 90 Hz performs comparably to 120 Hz while consuming less energy, making it especially ideal for text-only scrolling and fullscreen image scrolling scenarios. For text-based activities such as e-book reading or document browsing, where visual complexity is low and scrolling speeds are mostly moderate, 90 Hz can offer a smooth and positive experience. Similarly, when swiping through photo galleries or image-heavy interfaces, 90 Hz ensures fluid transitions and reduces motion blur during the browsing.

Second, for mixed text-and-image scrolling scenarios with interleaved visual elements of varying sizes and characteristics, a refresh rate of 120 Hz is recommended to minimise screen flicker and enhance smoothness. This is particularly important for interfaces such as e-commerce platforms, news feeds, or multimedia-rich web pages, where the diverse visual elements require greater consistency and seamless performance during scrolling.

Third, dynamic adjustment of refresh rates is essential for balancing user experience and energy efficiency, and therefore is recommended. However, changes in refresh rates should be made cautiously, particularly when lowering the rate, to avoid noticeable stuttering or flickering that could disrupt the user experience. Thus, dynamic refresh algorithms should be further explored and applied based on content and interaction speed to balance smooth scrolling experience and energy efficiency.

4.5. Limitations and directions for future research

One limitation of this study was the lack of precise control over the speed of user scrolling operations. Users were asked to scroll at both fast and slow speeds, as

well as freely scroll at their own pace during each scrolling trial, which was intended to replicate daily-life scrolling behaviour. However, it is important to note that scrolling speed has been found to have a positive relationship with the satisfied refresh rate (Han et al. 2013). Thus, when engaging in high-speed scrolling, the user experience associated with a 90 Hz refresh rate may differ significantly from that with a 120 Hz refresh rate, warranting further investigation.

Moreover, the present study focused on three specific refresh rates aligned with mainstream device settings, which may have excluded less conventional or emerging options (e.g. 144 Hz). Future research could explore a broader range of refresh rates and fine-grained levels to establish thresholds that optimise user experience across different scrolling tasks.

Further, the present study focused exclusively on one specific type of mobile device (mobile phone with a 6.7-inch AMOLED screen and a resolution of 3216×1440 pixels), without considering varying screen size, resolution and screen technologies. Previous studies have identified poor user experience, particularly when high-motion videos are displayed at lower refresh rates on larger screens (e.g. 15-inch laptops; Agboma and Liotta 2006). Thus, scrolling on devices with an increased field of view (e.g. foldable displays, tablets) may reveal more pronounced differences in user experience at higher refresh rates. Similarly, higher-resolution screens, which can display finer details, have been linked to enhanced subjective preferences (Chen and Chiang 2012), potentially increasing the likelihood of perceiving differences between higher refresh rates. In addition, different mobile display technologies can show varying performance, with (AM)OLED displays – prevalent in most contemporary mobile devices – providing better control of refresh rates and improved image quality compared to LCD displays (HONOR Club 2024). It is possible that on LCD displays and with lower screen resolutions, the advantages of higher refresh rate may be less noticeable due to lower contrast ratios and poor overall image quality, which could diminish the perceptibility of improvements in refresh rate. It would be valuable for future research to replicate our findings on devices with different specifications.

5. Conclusion

In conclusion, the present study investigated the effect of refresh rate on the touchscreen scrolling experience employing three typical daily-life scrolling tasks featuring texts and/or images. The findings demonstrated that refresh rates of 90 and 120 Hz improved perceived smoothness and reduced screen jittering during

scrolling compared to 60 Hz. However, there were negligible differences in subjective ratings between 90 and 120 Hz across most scrolling tasks. Moreover, users showed greater sensitivity to changes in refresh rate between 60 Hz and higher values than to changes within the 90 Hz to 120 Hz range, with this difference being more pronounced when the refresh rate decreased. Additionally, users displayed a more conservative response bias toward refresh rate decreases compared to increases in the specific scrolling task. These findings shed light on users' perceptual experience of scrolling with various refresh rates, and offer useful design guidelines for optimising the screen display of mobile devices.

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Appendices

Appendix 1

Table A1. Demographic details of users in each of the three scrolling tasks.

	<i>N</i>	Gender	Age range	Educational background	Occupation	Experience with mobile operating systems	Years of mobile phone use	Daily mobile usage time	Sensitivity to display or operation fluency
Users in the text-only scrolling task	51	females (N = 31) males (N = 20)	20–24 years old (N = 39) 25–29 years old (N = 9) 30–34 years old (N = 2) 39–44 years old (N = 1)	Below undergraduate (N = 1) Undergraduate (N = 20) Postgraduate (N = 30)	University student (N = 48) Others (N = 3)	iOS users (N = 11) Android users (N = 40)	<i>Mean</i> = 7.24 years (<i>SD</i> = 2.12)	Less than 1 h (N = 1) 1–3 h (N = 3) 3–5 h (N = 10) 5–8 h (N = 21) More than 8 h (N = 16)	Sensitive users (N = 40) Non-sensitive users (N = 11)
Users in the fullscreen image scrolling task	45	females (N = 27) males (N = 18)	20–24 years old (N = 31) 25–29 years old (N = 12) 30–34 years old (N = 2)	Undergraduate (N = 14) Postgraduate (N = 31)	University student (N = 43) Others (N = 2)	iOS users (N = 11) Android users (N = 34)	<i>Mean</i> = 7.67 years (<i>SD</i> = 2.25)	Less than 1 h (N = 1) 1–3 h (N = 2) 3–5 h (N = 8) 5–8 h (N = 17) More than 8 h (N = 17)	Sensitive users (N = 37) Non-sensitive users (N = 8)
Users in the text + image scrolling task	47	females (N = 28) males (N = 19)	20–24 years old (N = 34) 25–29 years old (N = 10) 30–34 years old (N = 3)	Below undergraduate (N = 1) Undergraduate (N = 16) Postgraduate (N = 30)	University student (N = 43) Others (N = 4)	iOS users (N = 10) Android users (N = 37)	<i>Mean</i> = 7.70 years (<i>SD</i> = 2.28)	Less than 1 h (N = 1) 1–3 h (N = 2) 3–5 h (N = 9) 5–8 h (N = 18) More than 8 h (N = 17)	Sensitive users (N = 40) Non-sensitive users (N = 7)
Tests for differences among users across the three scrolling tasks		$\chi^2(2) = 0.02$, $p = .992$	$\chi^2(6) = 0.02$, $p = .780$	$\chi^2(4) = 1.77$, $p = .778$	$\chi^2(2) = 0.67$, $p = .716$	$\chi^2(2) = 0.16$, $p = .922$	<i>all</i> $p > 0.290$ in the independent sample <i>t</i> -test	$\chi^2(8) = 0.61$, $p = .999$	$\chi^2(2) = 0.74$, $p = .691$

Note: **Sensitivity to display or operation fluency** was assessed based on the question 'What aspects of features are most important to you when purchasing a mobile phone?' which was collected before the experiment. Users who responded with key words such as 'operation fluency' and 'screen and display performance' were classified as sensitive users.

Appendix 2

Survey on the evaluation of smoothness and jittering & change detection

- Section 1:
 1. Please rate the level of perceived smoothness during scrolling. (Scores ranged between 1 and 5; 1 = ‘not at all smooth’, 5 = ‘extremely smooth’)
 2. Please rate the level of perceived screen jittering/flickering during scrolling. (Scores ranged between 1 and 7; 1 = ‘not at all jittery’, 7 = ‘extremely jittery’)
- Section 2:
 1. Did you notice any changes in the refresh rate while scrolling? (Yes/No)

Appendix 3

Table A2. Mean (SE) rating scores of perceived smoothness and perceived screen jittering in three refresh rates (60, 90, 120 Hz) and for each type of scrolling task.

	Type of scrolling task	Refresh rate		
		60Hz	90Hz	120Hz
Perceived smoothness	<i>text-only</i>	3.29 (0.13)	4.16 (0.07)	4.29 (0.09)
	<i>fullscreen image view</i>	3.49 (0.17)	4.27 (0.08)	4.38 (0.07)
	<i>text + image</i>	3.39 (0.17)	4.19 (0.08)	4.40 (0.09)
Perceived screen jittering	<i>text-only</i>	3.46 (0.24)	2.20 (0.18)	2.04 (0.18)
	<i>fullscreen image view</i>	3.18 (0.24)	1.89 (0.13)	1.84 (0.14)
	<i>text + image</i>	3.38 (0.26)	2.18 (0.16)	2.12 (0.18)

Appendix 4

Table A3. Results of one-way ANOVAs on the perceived smoothness and perceived screen jittering for each type for scrolling task, with refresh rate (60, 90, 120 Hz) serving as within-subjects factor.

	Type of scrolling task	Effect of refresh rate				post-hoc
		<i>F</i>	<i>df</i>	<i>p</i>	η_p^2	
Perceived smoothness	<i>text-only</i>	39.95	(2, 100)	<.001	0.44	60Hz < 90 Hz (<i>p</i> < .001), 60Hz < 120 Hz (<i>p</i> < .001), 90 Hz vs. 120 Hz (<i>p</i> = .480)
	<i>fullscreen image view</i>	26.81	(2, 88)	<.001	0.38	60Hz < 90 Hz (<i>p</i> < .001), 60Hz < 120 Hz (<i>p</i> < .001), 90 Hz vs. 120 Hz (<i>p</i> = .180)
	<i>text + image</i>	28.01	(2, 92)	<.001	0.38	60Hz < 90 Hz (<i>p</i> < .001), 60Hz < 120 Hz (<i>p</i> < .001), 90 Hz < 120 Hz (<i>p</i> = .006)
Perceived screen jittering	<i>text-only</i>	31.49	(2, 100)	<.001	0.39	60Hz > 90 Hz (<i>p</i> < .001), 60 Hz > 120 Hz (<i>p</i> < .001), 90 Hz vs. 120 Hz (<i>p</i> = .170)
	<i>fullscreen image view</i>	30.68	(2, 88)	<.001	0.41	60Hz > 90 Hz (<i>p</i> < .001), 60 Hz > 120 Hz (<i>p</i> < .001), 90 Hz vs. 120 Hz (<i>p</i> > .999)
	<i>text + image</i>	21.51	(2, 92)	<.001	0.32	60Hz > 90 Hz (<i>p</i> < .001), 60 Hz > 120 Hz (<i>p</i> < .001), 90 Hz vs. 120 Hz (<i>p</i> > .999)

Note. Bold values denote statistical significance at the *P* < 0.05 level.

Appendix 5

Detection sensitivity (d') in the change detection task

For the text-only scrolling task, a significant main effect of change interval was found ($F(2, 100) = 16.90, p < .001, \eta_p^2 = 0.25$). Post hoc analysis revealed that the sensitivity was the lowest for the change interval of 90 & 120 Hz (all $p < .001$), while no significant difference was observed between 60 & 120 Hz and 60 & 90 Hz ($p = .163$). The main effect of change direction was not significant ($F(1, 50) = 1.93, p = .171, \eta_p^2 = 0.04$). However, there was a significant interaction between change direction and change interval ($F(2, 100) = 4.75, p = .011, \eta_p^2 = 0.09$). Post hoc tests indicated that there were no significant differences in sensitivity when decreasing to 60 Hz from either refresh rates, as both conditions were associated with a higher sensitivity compared to when decreasing to 90 Hz from 120 Hz (all $p < .001$). In contrast, no significant differences in response sensitivity were observed across trial conditions with an increase in the refresh rate (all $p > .400$). Additional post hoc tests were conducted, which indicated higher sensitivity for refresh rates decreasing from 90 Hz to 60 Hz compared to those increasing from 90 Hz to 120 Hz ($p = .001$). There were no significant differences between refresh rate increases and decreases within the same range (all $p > .200$).

For the fullscreen image scrolling task, a significant main effect of change interval was found ($F(2, 88) = 6.12, p = .003, \eta_p^2 = 0.12$). Post hoc tests indicated significantly higher sensitivity in the trial conditions where the change interval varied between 60 and 90 Hz, as well as between 60 and 120 Hz, compared to the trial condition of 90 & 120 Hz (all $p < .050$). No significant difference was observed between 60 & 120 Hz and 60 & 90 Hz ($p > .999$). There was no significant difference in sensitivity between the trial conditions of 60 & 90 Hz and 60 & 120 Hz ($p > .999$). The main effect of change direction was not significant ($F(1, 44) = 1.41, p = .241, \eta_p^2 = 0.03$). However, the interaction between change direction and change interval was marginally significant ($F(2, 88) = 2.44, p = .093, \eta_p^2 = 0.05$). Post hoc tests indicated that decreasing to 60 Hz from either refresh rates was associated with a higher sensitivity compared to decreasing to 90 Hz from 120 Hz (all $p < .050$). However, no significant differences in sensitivity were observed across trial conditions with an increase in the refresh rate (all $p > .999$). Additional post hoc tests were conducted, which indicated higher sensitivity for refresh rates decreasing from 90 Hz to 60 Hz compared to those increasing from 90 Hz to 120 Hz ($p = .014$). There were no significant differences between refresh rate increases and decreases within the same range (all $p > .600$).

For the text + image scrolling task, there was a significant main effect of change interval ($F(2, 92) = 20.22, p < .001, \eta_p^2 = 0.31$). Post hoc tests showed significantly higher sensitivity in the trial conditions of 60 & 120 Hz and 60 & 90 Hz, compared to the trial condition of 90 & 120 Hz (all $p < .001$). No significant difference was observed between 60 & 120 Hz and 60 & 90 Hz ($p = .130$). The main effect of change direction was not significant ($F(1, 46) = 1.31, p = .258, \eta_p^2 = 0.03$). However, there was a marginal interaction between change interval and change direction ($F(2, 92) = 2.57, p = .082, \eta_p^2 = 0.05$), with higher sensitivity when decreasing to 60 Hz from either refresh rates, compared to decreasing to 90 Hz from 120 Hz (all $p < .010$). Moreover, a higher sensitivity was also observed in the trial condition where the refresh rate increased from 60 to 120 Hz compared to trials where the refresh rate increased from 90 to 120 Hz ($p = .005$). Additional post hoc tests were conducted, which indicated higher sensitivity for refresh rates decreasing from 90 to 60 Hz compared to those increasing from 90 to 120 Hz ($p = .002$). There were no significant differences between refresh rate increases and decreases within the same range (all $p > .700$).

Appendix 6

Response bias (β) in the change detection task

For the text-only scrolling task, none of the main effects (change interval and change direction) or their interaction reached statistical significance (all $F < 1$).

For the fullscreen image scrolling task, the analysis revealed a significant main effect of change direction ($F(1, 44) = 6.36, p = .015, \eta_p^2 = 0.13$), indicating that there were higher β values when there was a decrease in the refresh rate compared to when there was an increase in the refresh rate. However, the main effect of change interval was not significant ($F(2, 88) = 1.71, p = .187, \eta_p^2 = 0.04$). Change direction significantly interacted with change interval ($F(2, 88) = 4.36, p = .016, \eta_p^2 = 0.09$). None of the post hoc pairwise comparisons reached statistical significance (all $p > .050$). We observed a trend towards slightly higher β values when the refresh rate decreased to 60 Hz from 90 Hz, compared to when it increased to 90 Hz from 60 Hz ($p = .061$). Additionally, increasing the refresh rate from 90 Hz to 120 Hz was associated with slightly higher β values compared to increasing the refresh rate from 60 Hz to 90 Hz ($p = .061$).

For the text + image scrolling task, the analysis did not reveal any significant effects. Neither the main effect of change interval ($F(2, 92) = 2.23, p = .114, \eta_p^2 = 0.05$), nor the main effect of change direction ($F < 1$), were found to be significant. Additionally, the interaction between change interval and change direction was not statistically significant ($F(2, 92) = 1.94, p = .150, \eta_p^2 = 0.04$).

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