Effect of Frame Rate on User Experience, Performance, and Simulator Sickness in Virtual Reality

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Abstract— The refresh rate of virtual reality (VR) head-mounted displays (HMDs) has been growing rapidly in recent years because of the demand to provide higher frame rate content as it is often linked with a better experience. Today's HMDs come with different refresh rates ranging from 20Hz to 180Hz, which determines the actual maximum frame rate perceived by users' naked eyes. VR users and content developers often face a choice because having high frame rate content and the hardware that supports it comes with higher costs and other trade-offs (such as heavier and bulkier HMDs). Both VR users and developers can choose a suitable frame rate if they are aware of the benefits of different frame rates in user experience, performance, and simulator sickness (SS). To our knowledge, limited research on frame rate in VR HMDs is available. In this paper, we aim to fill this gap and report a study with two VR application scenarios that compared four of the most common and highest frame rates currently available (60, 90, 120, and 180 frames per second (fps)) to explore their effect on users' experience, performance, and SS symptoms. Our results show that 120fps is an important threshold for VR. After 120fps, users tend to feel lower SS symptoms without a significant negative effect on their experience. Higher frame rates (e.g., 120 and 180fps) can ensure better user performance than lower rates. Interestingly, we also found that at 60fps and when users are faced with fast-moving objects, they tend to adopt a strategy to compensate for the lack of visual details by predicting or filling the gaps to try to meet the performance needs. At higher fps, users do not need to follow this compensatory strategy to meet the fast response performance requirements.

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1 INTRODUCTION

Refresh rate and frame rate are two critical factors that affect users' experience when viewing interactive content via a screen display. The refresh rate of a display (expressed in Hz) is the number of times per second that the image refreshes on the screen and the frame rate (expressed in fps) is the frequency of the frames displayed within a second. People have the ability to distinguish between different frame rates and normally prefer a higher frame rate because a higher frame rate improves the quality of motion perceived by people [11,22]. As shown in Fig. 1 (a), a higher frame rate can demonstrate more frames to show an object's motion, making the movement perceived to be more continuous and smooth (that is, more realistic). Normally, an application can be rendered at the highest frame rate that a GPU allows. However, the refresh rate of a display determines the actual maximum frame rate perceived by users' naked eyes. This can explain why eSports participants and gamers typically want higher refresh rate monitors when playing video games [35].

The market of virtual reality (VR) head-mounted display (HMD), a relatively newer display type that provides immersive experiences, has grown rapidly. Unlike traditional 2D displays for desktops/laptops, VR HMDs usually require a high refresh rate and resolution to ensure a satisfactory user experience, particularly in lowering simulator sickness (SS), a condition that affects a large population of users [31]. Fig. 1 (b) shows the summary of the refresh rate of 101 released and available VR HMDs from 1989 to 2022.[1] As the figure shows, the refresh rate has risen steadily over the last two decades with 90Hz still the most common and 180Hz the highest. It is foreseeable that new VR HMDs with higher refresh rates will be released in the future.

VR applications, especially those with fast-paced content such as games, usually require a trade-off between higher resolution and frame rate because of the high computational requirements of displaying their content and users' interaction with it [29,43]—in other words, it is technically challenging and costly to have both high resolution and refresh rate within current HMDs. Just like general video games, such a trade-off is also an issue for VR games since advances in hardware capabilities often fall behind the computational requirements needed for higher graphics output [9]. Although super sampling, such as NVIDIA Deep Learning Super Sampling (DLSS) and AMD FidelityFX Super Resolution (FSR), can increase frame rate to relieve such a tradeoff to some extent, it can cause a slight downgrade in graphics quality [41]. Against such a background, it is important to ascertain in detail the benefits and often trade-offs of higher resolution and frame rate of current VR HMDs. A recent study demonstrated that 2K represents the lower resolution threshold for an enhanced user experience, particularly in games, without affecting performance and increasing users' SS levels during interaction [37]. On the other hand, frame rate and its effect on user experience, performance, and SS levels in VR HMDs have not been explored in detail.

As mentioned, VR HMD's refresh rate decides the maximum frame rate that can be perceived. 180Hz is the highest refresh rate of all currently available VR HMDs (see Fig. 1 (b)), which would support a wide range of frame rates. It is important to know how frame rates of VR HMDs affect overall user experience and performance, which are two important factors in the adoption of VR in general and VR games in particular, just like with traditional games. Moreover, the effect of the frame rate of VR HMDs can help users to choose a suitable frame rate and resolution to achieve optimal performance and experience if they know their trade-offs. Similarly, this understanding allows VR HMD and content developers to optimize their setup and minimize costs associated with higher refresh rates if it is not necessary for the experience they want to provide to users. This work aims to investigate the underexplored effect of frame rate on user experience and performance in VR HMDs.

This research involves a user study with two VR applications to investigate the effect of frame rate on users' experience, performance, and SS symptoms. The two VR applications contain elements from var-

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[1] A detailed comparison of all specifications is available on `https://vr-compare.com/vr`.

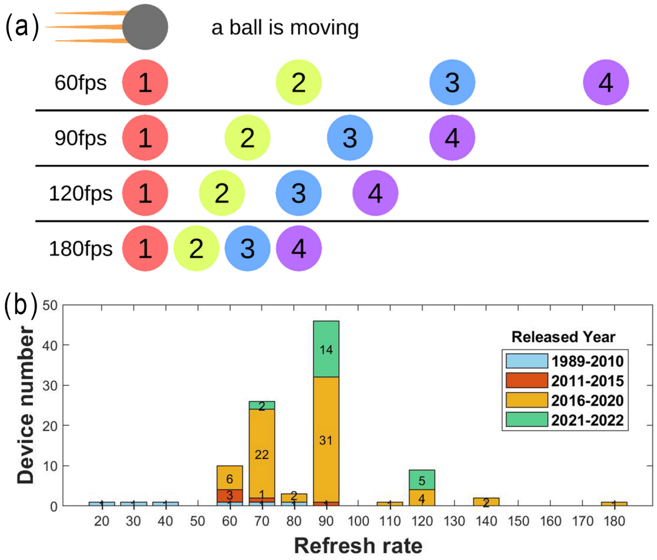

Fig. 1: (a) Stroboscopic flash photographs of a moving ball under different frame rates. The photographs are simulated with a virtual 2D camera that uses orthographic projection. The numbers (1-4) are the frame IDs. (b) Stacked bar chart of the number of released and available VR HMDs with different refresh rates.

ious use case scenarios, including games. They represent two distinct subsets that require (and do not require) users to observe precisely the visual details of moving objects in VR environments. Our user study compared frame rates of 60fps, 90fps, 120fps, and 180fps, which represent both typical and the highest settings among different HMDs. In addition, our applications used dynamic objects with different moving speeds (10m/s, 20m/s, 30m/s, and 40m/s) because dynamic content can help us investigate the effects of frame rates on user performance more precisely. The results indicate that 180fps and 120fps produced significantly lower SS symptoms than 60fps. They also show that 120fps and above would not cause a negative effect on the overall experience as much as 60fps and 90fps. That is, users will feel fewer SS symptoms without a significant negative effect on their overall experience. Higher rates (e.g., 120-180fps) seem to support better user performance (especially compared to lower fps). Finally, another interesting finding is that 60fps could make users choose a different strategy compared to higher fps, especially when dealing with fast-moving objects (e.g., at 40m/s) that require a quick response action from users.

In short, this work makes the following three main contributions:

- We demonstrate that 120fps is an important rate to have because users' performance data indicate that higher rates (especially 120-180fps) are helpful if the main aim is to support enhanced performance (i.e., higher accuracy and faster reaction) without decreasing overall experience.
- We introduce a new metric, Total Frame Fusion (TFF), for evaluating user performance on dynamic objects with different speeds under different frame rates. TFF can be regarded as the total amount of visual information of a dynamic target that can be perceived by users under a specific distance interval.
- We show that for dynamic objects (especially for objects with high speed such as 40m/s) rendered at 60fps, the insufficient visual information and the need for rapid reaction could make users change their strategy, to one that would rely more on predicting or filling missing gaps in the perceived visual information of fast-moving objects.

2 RELATED WORK

2.1 Effect of Frame Rate in Non-VR environments

Much of the research looking at the effect of frame rates, especially low rates, on non-VR displays took place two decades ago during the time when PCs gained importance. At that time, the displays (i.e., computer monitors) were based on Cathode Ray Tube technology [40]. Some research suggests that 10fps is the minimum threshold to meet the performance requirements (e.g., response time and accuracy) for fundamental, basic tasks such as object tracking or placement [6, 8, 39]. However, 15fps is more acceptable for better performance in other more complex tasks that emphasize perceiving greater detail, such as target recognition, text reading, and watching videos [4, 13, 18, 23].

Advances in the last two decades have improved display technology allowing for much higher frame rates. A high frame rate typically provides a better experience for different application scenarios, especially for fast-paced video games such as first-person shooter games. Early in 2006, Claypool et al. [9] found that first-person shooter games with 30fps and 60fps frame rates can result in a better player performance than with 15fps. First-person shooter games have become one of the most popular game genres in eSports competitions. They typically require a fast response time from players [33]. Prior work has found that players' response time in these games can be decreased by using higher refresh rate monitors with short latency [35]. This made high refresh rate monitors, which would ensure high frame rates, popular in eSports competitions [27] and for general gamers who want an optimal experience. Murakami and Miyachi [27] claimed that 120Hz or above could significantly improve eSports participants' performance. Latency caused by other reasons can also affect players' performance [34]. Moreover, Duinkharjav et al. [12] proved that image features can influence reaction time. Furthermore, latency is also an important factor for Foveated Rendering which is related to render resolution in VR [3]. The above existing research about visual perception focuses on the analysis of basic metrics such as latency and reaction time. We introduce a new metric to quantify and analyze the specific visual information perceived by users during specific interactions in our work. In general, advances in hardware and gamers' demand for better gameplay experiences and performance have been two primary motivators for using high frame rates in displays. However, the hardware needed to support higher frame rates tends to be more expensive and bulkier/heavier.

2.2 Effect of Frame Rate in VR HMDs

Research on the effect of frame rates in VR HMDs is similar to what has been done in non-VR environments. The first explorations were conducted around 2000 when 60fps was considered high [1, 38]. This early research showed that the high latency from low frame rates was one of the main causes of degradation in user experience and performance [38]. This perspective has been accepted by later research. For example, in 2003, Meehan et al. [24] conducted an experiment to compare the effect of a low latency condition (50ms, ∼20fps) and a high latency condition (90ms, ∼11fps) with a 60Hz refresh rate display on users' physiological response, SS, and self-reported sense of presence. They found that participants in the low latency condition had a higher self-reported sense of presence and a greater change in their heart rates than those in the high latency condition. However, they did not find significant relationships between latency and SS. As their research was conducted with equipment that is more than two decades old, it is not clear if the same findings hold for today's HMDs. For example, 20fps and 11fps are very low compared to current VR HMDs' refresh rates (see Fig. 1 (b)). Similarly, other aspects (e.g., resolution) are likely not as developed as in today's HMDs. To the best of our knowledge, no recent research has looked in detail at the effects of the frame rate of current VR HMDs, especially in demanding and fast-paced task scenarios that are involved in but not exclusive to games.

2.3 Evaluation of Simulator Sickness, Game Experience, and User Performance

Meehan et al. [24] used three post-experience measurements, including SS, self-reported presence, and self-reported fear, while none of them significantly varied between the two latency groups in their experiment. One possible reason is that the frame rates in both conditions are low, which may not have significant effects. In this paper, we are also interested in the effects of frame rate on SS in VR applications. The Simulator Sickness Questionnaire (SSQ) is a common instrument to measure SS [16] and has been used widely—as such, it is also used in this research. Besides, a fast-paced VR task scenario can help test the effect of frame rate better, as mentioned in the previous sections. Gaming aspects involving fast-paced response actions and object movements in the VR environment are suitable for such explorations and results can be applied to other non-gaming scenarios. We developed two VR applications that include elements from VR games to evaluate the effects of frame rate (described in Sect. 3). Game experience in different frame rate conditions is another measurement we considered. We used the revised version of Game Experience Questionnaire (GEQ) [15], a popular questionnaire for the measurement of gaming experience [5, 14, 19, 30].

We also measured performance in terms of accuracy and reaction time according to the tasks of each of the two applications. Currently, a common approach to compare the effect of different frame rates on dynamic objects is to use simulated stroboscopic flash photography under *orthographic projection* via a 2D camera, as shown in Fig. 1 (a). A higher frame rate reasonably results in a short frame interval. However, for a 3D virtual environment that uses *perspective projection* via a 3D camera, we need to measure the difference in frame rates when applied to objects moving at different speeds in a better way. To meet this need, in this work we also developed a new measurement that would allow quantifying the effect of the frame rates and objective comparison between them. We describe the performance metrics in Sect. 3.5 in detail.

2.4 Research Questions

Based on our literature review and the gap we identified, we formulated these two research questions that will be explored by two related VR applications that have the same controlled variables (see Sect. 3):

- **RQ1**. Is there a frame rate threshold for VR applications that require a fast response time but *do not need users to focus on the visual details*, after which the benefits of higher frame rates on users' performance and experience (including SS) become non-significant? Results from the first (fruit cutting) application (see Sect. 3.2) answer this RQ.

- **RQ2**. Is there a frame rate threshold for VR applications that require a fast response time and *need users to focus on visual details*, after which the benefits of higher frame rates on their performance and experience become non-significant? Results from the second (dynamic vision) application (see Sect. 3.3) answer this RQ.

3 USER STUDY

To investigate the above two research questions, we developed two VR applications that include elements representative of various VR scenarios. The two applications are designed to involve moving objects and require participants to perceive the objects with varying degrees of detail. Participants would react to the dynamic targets with different moving speeds and complete the given tasks in four frame rate conditions. In this section, we introduce these two application scenarios and other experimental settings in the user study.

3.1 Participants and Apparatus

Thirty-two participants (16 females, 16 males) were recruited from a local university. Participants' age ranged between 18 and 31 ($M = 20.63, SD = 2.18$). All of them had normal or corrected-to-normal eyesight, no history of color blindness, and no declared mental or physical health issues according to the data gathered from a pre-experiment questionnaire. We also collected participants' prior VR gaming experiences in this questionnaire. 21 participants played VR games before the experiment. The experiment was classified as low-risk research, was carried out in compliance with Xi'an Jiaotong-Liverpool University's ethics guidelines and regulations, and was approved by its University Ethics Committee. All participants gave their consent to participate in the experiment.

Fig. 2: A picture of the experimental setup and equipment used.

We used Pimax 5K Super as our VR HMD since it has the highest refresh rate (180Hz) among all available VR HMDs according to Fig. 1 (b). It has a resolution of 2560×1440 (2.5K) per eye, and a field-of-view of 200°(D)/170°(H)/115°(V). These parameters were fixed for the two VR applications in this user study. The Pimax HMD was connected to a desktop with 16GB RAM, a GeForce RTX 2080Ti GPU, and an Intel Core i7-9700K CPU. We used two HTC Vive controllers and an Xbox controller as the input devices and two HTC SteamVR base stations for tracking which was the setup recommended by the company.[2] The user study was conducted in an empty room with controlled light and temperature. Fig. 2 shows the overall setup. The VR applications were developed with Unity3D (version 2020.3.30f1).

3.2 Application 1: Fruit Cutting Task

Application 1: Fruit Cutting Task (A1:FC) is inspired by a popular fast-paced game—*Fruit Ninja*, in which the main task is cutting flying fruits [2]. It has been used in many studies conducted in both non-VR and VR environments (e.g., [10, 17, 21, 42]). We adapted the game to produce a more controlled scenario to avoid unintended confounding variables and allow gathering data for measuring user performance and experience that is more generalizable.

In this application, participants would need to cut flying fruits in the specified cutting area, which is represented using a 1m^3 red cube 0.5m in front of users' view (see Fig. 3). The fruit spawner is placed on the right side of the cutting area and 50m away from the participants. The spawner can spawn five types of fruits, including bananas, apples, peaches, pears, and watermelons. Though the mesh of these different fruits is slightly different, all of them have the same sphere collider with a radius of 0.31m. Each fruit flies at a constant speed (introduced in Sect. 3.4) in a straight line from the spawner to the center of the cutting area and continues flying after crossing the cutting area. Participants would hold the controller (visualized as a sword), target the flying fruit, and cut the fruit vertically when the fruit passes through the cutting area, as shown in Fig. 3. The next fruit spawns after a fixed 1.5-second interval. A1:FC can be a representative sample of VR scenarios that require users to respond to moving objects but with a lower requirement to observe their details very clearly.

3.3 Application 2: Dynamic Vision Task

Dynamic vision is people's vision of dynamic objects such as a baseball moving through the air when thrown by a pitcher during a game [20]. The frame rate can affect users' performance in virtual scenarios that involve dynamic vision to some extent, particularly when users need

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[2] `https://support.pimax.com/en/support/home`

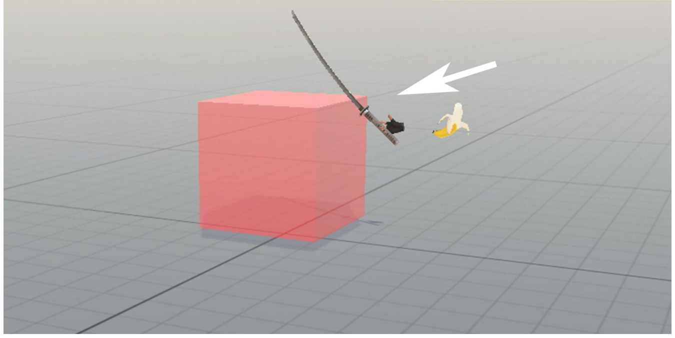

Fig. 3: A third-person perspective screenshot of Application 1 (A1:FC) A fruit (banana) flies from right to left through the red cutting area, and the participant holds a sword aiming to cut it.

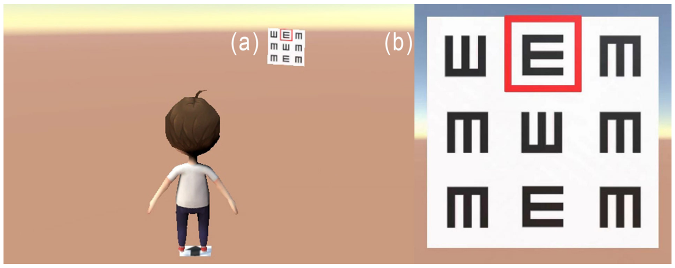

Fig. 4: A third-person perspective screenshot of Application 2 (A2:DV), where (a) a modified Tumbling E Chart (TEC) is flying toward a participant (visualized using an avatar); and (b) a front view of a TEC.

to observe the details of the moving objects quickly, such as in first-person shooter games to identify weapons and different types of players from a distance. This aspect is not covered in the first application. We considered using *Beat Saber* since this VR game contains dynamic objects that require users to perceive their details. However, it is a music and rhythm game that challenges users' sense of rhythm. After exploring several possibilities, we decided to use a modified Tumbling E Chart (TEC) [28] as the dynamic targets or objects whose details would need to clearly perceived by users. In addition, by using TECs, we were able to design this application that would follow a similar gameplay process as in *Beat Saber* but without rhythm and music elements to avoid confounding variables.

In Application 2: Dynamic Vision task (A2:DV), participants would need to perceive the orientation of the E letter from a modified TEC that is flying towards them. The modified TEC includes three rows and three columns, which gives a total of nine images of rotated E letters in a 0.4m^2 area (1.2m^2 for all nine images) where the limbs of the E can be upward, downward, leftward, or rightward that are randomly generated (see Fig. 4). Of the nine E-letter images, one is randomly selected as the target, and its borders are highlighted in red. The TEC is instantiated at a random position but initially placed 50m away from the participants and within their field-of-view (see Fig. 4). It flies towards the participants at a constant speed (introduced in Sect. 3.4). Participants would need to specify where the limbs of the target E are pointing by pressing the corresponding directional button on the Xbox controller immediately after they have identified its pointing direction. Similar to A1:FC, the next target spawns after a 1.5-second interval. We provided a tutorial before the formal trials to ensure that participants understood the task and could correctly match the directional buttons on the Xbox controller with the directions of the target E's limbs. Compared to A1:FC, A2:DV represents typical VR scenarios that require users to observe the details of moving objects carefully to determine the correct course of action.

We researched the literature to find a standardized way of measuring visual information for this type of dynamic task in VR but did not find any common measurements. Given the need to quantify users' performance in different frame rates and with objects moving at different speeds, we developed a new metric (see Sect. 3.5.3).

3.4 Study Design

This study used a 4×4 within-participants design with FRAME RATE (60, 90, 120, and 180fps) and OBJECT SPEED (10, 20, 30, and 40m/s) as the two independent variables.

VR HMD manufacturers often use the driver to limit the maximum frame rate according to the refresh rate. In other words, we can also control the frame rate by controlling the refresh rate. According to Fig. 1 (b), 90Hz is now the most common, popular high refresh rate. We can regard it as the mainstream refresh rate. 120Hz is the second most popular high refresh rate. It could be the next mainstream refresh rate and may replace 90Hz in the near future. 180Hz is the highest refresh rate among all released and available VR HMDs and, while it will take longer for it to become common, the trend is moving toward its adoption. 60Hz is still a popular fps setting for normal video games and non-VR displays used for desktops and laptops. Although 60Hz is not a popular refresh rate in VR HMDs, it may reveal the effect of a low frame rate in VR applications, especially because users are quite familiar with it in non-VR displays. Therefore, we set out to explore four conditions corresponding to 60fps, 90fps, 120fps, and 180fps in the user study. We tried to make the refresh rate equal to the frame rate. However, the Pimax 5K Super's driver only provided 90, 120, and 180Hz refresh rates and did not have the corresponding refresh rate for the 60fps condition. Given this, we had to set the frame rate of the application to 60fps under the lowest 90Hz refresh rate provided by the Pimax HMD. The detailed procedure to achieve this is provided in Appendix A, which allows other researchers to reproduce this setting.

In our scenarios, OBJECT SPEED was the fruits' moving speed in the A1:FC and the TEC's moving speed in the A2:DV. The four speeds were tested and determined via a pilot study (N=6); they also represented possible object speeds in various types of VR applications. Data from pilot trials were used to ensure that participants could see the objects at the fastest 40m/s speed with the highest 180Hz refresh rate in both VR applications. According to the feedback and data of the pilot trial participants, speeds higher than 40m/s were too challenging for a distance of 50 meters. Therefore, we did not use speeds higher than 40m/s to ensure that the speeds would be reasonable and practical. We also paid close attention to two factors: *object size* and *distance*, which were related to the visual information perceived by potential participants (see Sect. 3.5.3). Different object sizes and distances may have different feasible speed ranges. In addition, we ensured that an object with the slowest speed (i.e., 10m/s) could be observed clearly in all FRAME RATE conditions. The time of each repetition is fixed regardless of participants' input; that is, the difference in individual performance (faster or slower to react to the moving object) would not affect their exposure to the VR applications.

Each FRAME RATE×OBJECT SPEED condition contained 20 repetitions (i.e., 20 fruits in A1:FC and 20 TECs in A2:DV). In total, we collected 10240 trials of data for each scenario (=32 participants × 4 frame rates × 4 object speeds × 20 repetitions).

3.5 Evaluation Metrics

3.5.1 Subjective Measures

We also compared the effects of the frame rate based on subjective measures, including simulator sickness (SS) and game experience, measured via a Simulator Sickness Questionnaire (SSQ) [16] and a revised Game Experience Questionnaire (GEQ) [15]. A pre-SSQ was given before the trials, while SSQ and GEQ were given after each FRAME RATE condition. Data collected from SSQ was computed into four sub-scores: Total Severity, Nausea, Oculomotor, and Disorientation. GEQ contained five factors: flow, immersion, competence, positive affect, and negativity.

3.5.2 User Performance

We used three metrics to measure participants' performance in the two applications: *accuracy*, *reaction distance*, and *effective reaction*

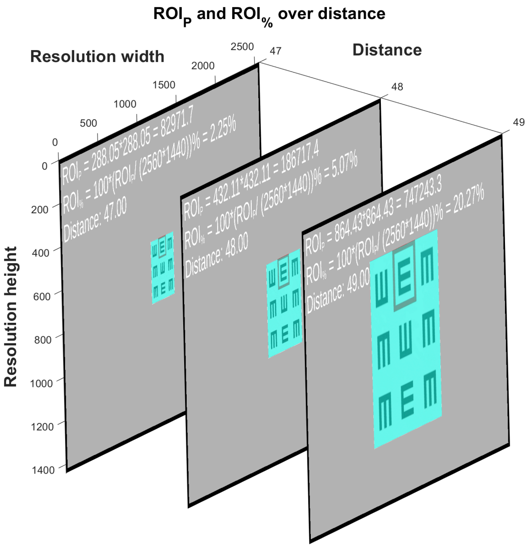

Fig. 5: An example of the region of interest (ROI) in A2:DV. The ROI (visualized as the size of the cyan areas) increases as its moving distance increases; that is, it moves closer to the participant. The calculations and values of ROI_P and $ROI_\%$ under three example distances are shown in the figure.

distance. Before introducing these measurements, we defined trials where participants successfully cut the fruit or correctly answered the orientation of E as *successful trials*. Accuracy was the number of successful trials out of the total number of trials in each FRAME RATE×OBJECT SPEED condition. In A1:FC, the reaction distance was the distance between the center of the fruits and the center of the cutting area when the sword first collided with the cutting area, i.e., where the participants intended to cut the fruit. In A2:DV, the reaction distance was the distance between the TEC and the participants when they pressed the button on the controller to answer the direction of the target E. The reaction distance is also equal to 50m - the TEC displacement in A2:DV. The average reaction distance among all the trials in each application was used. Besides, we also measured effective reaction distance, which was the average reaction distance in the successful trials.

3.5.3 Total Frame Fusion: a new measurement to quantify the effects of frame rate and speed

We introduce *Total Frame Fusion* (TFF), a new metric to quantify the effects of frame rate on moving objects. TFF can be regarded as total visual information of a dynamic target under a specific distance interval (displacement of target) perceived by a user. A smaller TFF means a better dynamic vision with higher prediction ability. In other words, less visual input information is required to observe the moving object clearer and react to it faster. In this section, we introduce how it is derived.

In image processing, a region of interest (ROI) is used to select a portion of an image that needs to be operated on. For A2:DV, the target panel was generated within the participants' field of view and moved straight toward the participants. The participants would keep watching the panel during this process. In this case, we can use the size of a rectangular ROI in pixels ($ROI_{Res.height} * ROI_{Res.width}$) to represent the actual image size of the panel in each frame (see Fig. 5). With the continuous movement of the TEC, the ROI would keep updating with the panel position in each frame. Since the display resolution was kept constant in our experiment ($Display_{Res.horizontal} * Display_{Res.vertical}$, which equals to 2560×1440), we could divide the *ROI image resolution* (ROI_{Pn}) by the display resolution to get an *ROI image ratio* ($ROI_{\%n}$) at frame *n*, as described in Equation 1. $ROI_\%$ can be used as an alternative scientific notation to ROI_P since the latter can have a large number, which can make its demonstration and interpretation inconvenient (see Fig. 5, using $ROI_\%$ is more efficient than ROI_P to some extent, see the $ROI_\%$ examples in Fig. 5).

$$\begin{aligned} ROI_{Pn} &= ROI_{Res.height} * ROI_{Res.width} \\ ROI_{\%n} &= \frac{ROI_{Pn}}{Display_{Res.horizontal} * Display_{Res.vertical}} * 100\% \end{aligned} \tag{1}$$

Though the object's movement can be perceived as continuous, it can be discretized using a *distance unit* for a certain frame rate and object speed. Among all conditions, the *minimum distance unit* in our case is when the frame rate is 180fps and the object speed is 10m/s. We formulate the distance sampling size as $k\times$ minimum distance unit, where k is a constant and $k \in (0,1)$. This is to ensure the distance sampling size is always smaller than the minimum distance unit so that ROI_P can be generated accurately for all conditions. In addition, the smaller k, the more accurate ROI_P. In our case, we used a k of 0.1.

We then define a set X, which contains m multiples of distance sampling size (denoted as *distance*) within the total distance range (0–50m in our case). We also define a set Y, which contains ROI_P from frame 0 to frame n. Each ROI_P corresponds to one frame that has multiple *distance*. We use the recorded TEC displacement under reaction distance to map all conditions by a function from set X to set Y, as shown in Equation 2.

$$\begin{aligned} X &= \{distance_0, \ldots, distance_m\} \\ Y &= \{ROI_{P0}, \ldots, ROI_{Pn}\} \\ f(x) &= y, x \in X, y \in Y \end{aligned} \tag{2}$$

The ROI_P increases with the *distance*. In fact, the participants watched a series of continuous frames before selecting the direction of the target E image. Therefore, we compute the approximate cumulative integral of Equation 2 via the trapezoidal method to represent the Total Frame Fusion, as described in Equation 3 (px denotes pixel).

$$\begin{aligned} &\int_a^b f(x)dx \approx T_n = \\ &\frac{\triangle x}{2}[f(x_0) + 2f(x_1) + 2f(x_2) + \ldots .2f(x_{n-1}) + f(x_n)] \end{aligned} \quad [\text{px}\cdot\text{m}] \tag{3}$$

To help understand the new metric, we visualize Equation 2 and Equation 3 in Fig. 6. In a certain FRAME RATE×OBJECT SPEED condition, the area under the ROI_P line (i.e., the ladder pattern) represents Equation 3, that is, the TFF over a specific distance. As can be seen from the figure, a higher frame rate and a lower speed lead to 'smaller steps' of the ladder patterns with smaller TFF and vice versa. For example, a frame rate of 180fps with a moving speed of 10m/s would lead to the smallest step and smallest TFF, while 60fps with 40m/s would cause the biggest step and largest TFF. In an ideal condition with an infinite frame rate, the line should be a smooth curve with the maximum TFF.

We only applied TFF analysis for A2:DV since the targets in A1:FC have different shapes and fly from right to left rather than distant to near in front of users. Both the TEC displacement under reaction distance and the effective reaction distance can be applied to Equation 3 as the input distance.

3.6 Procedure

We split the user study into two sessions, which were separated by at least 24 hours, to prevent the accumulation of SS. Participants used A1:FC in the first session and A2:DV in the second session. On the first day, we collected participants' information via a demographic questionnaire and then briefed them on the procedure of the whole study. The remaining procedure was the same for the two sessions. Participants first received a tutorial about each application, including their tasks and the controls. Participants then filled in a pre-SSQ and

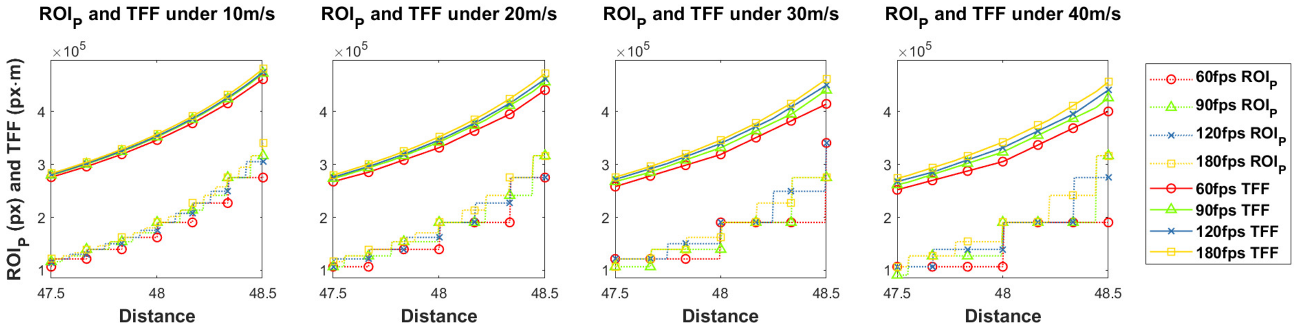

Fig. 6: An example of ROI pixels (*ROI$_P$*) and Total Frame Fusion (TFF) over distance under 4 frame rates (60, 90, 120, and 180fps) and 4 object speeds (10, 20, 30, and 40m/s). The ladder patterns in the figures indicate that *ROI$_P$* can remain unchanged over a distance interval due to a low frame rate and/or a high moving speed, which may explain why people can distinguish between different frame rates.

started to complete the formal trials. The order of FRAME RATE conditions was counterbalanced via a balanced Latin square design. In each FRAME RATE condition, the order of OBJECT SPEED condition was fixed, from slower speed to faster speed, representing tasks in order of complexity. After each FRAME RATE condition, the participants were required to complete an SSQ and a GEQ to measure their subjective feelings. OBJECT SPEED condition was only used to help us investigate the effects of frame rate on user performance. Therefore, it did not require collecting SSQ and GEQ because it would make the experiment exceedingly long, which would affect the overall performance and user experience. After the participants completed the trials in all conditions, we conducted a short interview to collect their feelings about different FRAME RATE conditions and feedback. Participants were naive to the purpose of the experiment in that we did not tell them how each condition should (or should not) lead to any expected behavior. The experiment lasted about 30 minutes for each session.

4 RESULTS

Non-parametric Friedman tests were performed for data collected via the SSQ and GEQ. Post-hoc analyses with Wilcoxon signed-rank tests were conducted with Bonferroni corrections. Our parametric user performance data are normally distributed according to the Kolmogorov-Smirnov test. We applied two-way repeated measures (RM-) ANOVA for parametric user performance data from both VR applications. When there is violation of the assumption of sphericity, we reported the degrees of freedom with Greenhouse-Geisser corrections ($\varepsilon < 0.75$) or Huynh-Feldt corrections ($\varepsilon > 0.75$). We also reported the effect size for significant results (Kendall's W for Friedman tests and partial eta squared for RM-ANOVA tests).

4.1 Application 1: Fruit Cutting Task

4.1.1 Subjective Measures

Fig. 7 provides a summary of the SSQ and GEQ data for A1:FC. The Friedman tests revealed statistically significant differences in Total Severity ($\chi^2(3) = 10.752, p = 0.013, W = 0.112$), Nausea ($\chi^2(3) = 10.672, p = 0.014, W = 0.111$), Oculomotor ($\chi^2(3) = 9.437, p = 0.024, W = 0.098$), and Disorientation ($\chi^2(3) = 11.004, p = 0.012, W = 0.115$) among the FRAME RATE conditions. Post-hoc analyses showed significant differences between 120fps and 60fps in Total Severity ($Z = -2.785, p = 0.005$; 120fps: $Mdn = 11.22$, 60fps: $Mdn = 31.79$), Oculomotor ($Z = -2.761, p = 0.006$; 120fps: $Mdn = 15.16$, 60fps: $Mdn = 26.53$), and Disorientation ($Z = -2.707, p = 0.007$; 120fps: $Mdn = 13.92$, 60fps: $Mdn = 27.84$), with 120fps leading to lower scores.

Results from the Friedman tests indicated statistically significant differences in negativity scores ($\chi^2(3) = 9.115, p = 0.028, W = 0.095$) among the FRAME RATES conditions, but post-hoc tests did not show significant differences. For the remaining aspects in GEQ, no significant differences of FRAME RATE were found ($p > 0.05$).

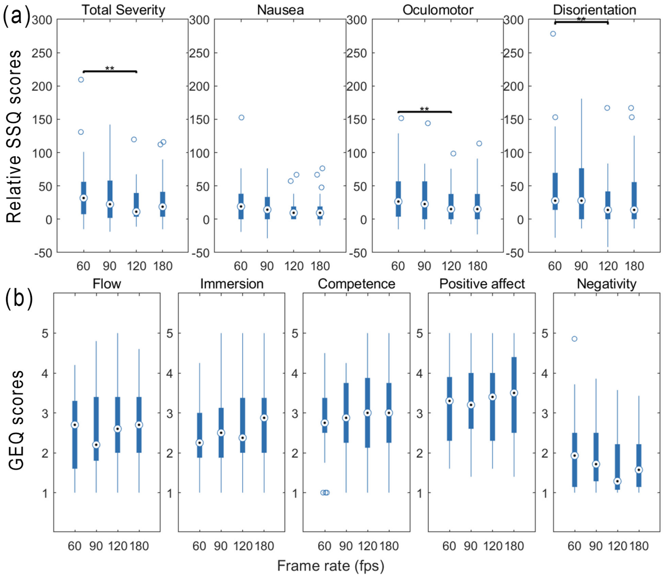

Fig. 7: Box plots of (a) the four relative SSQ sub-scores; and (b) the five GEQ sub-scores from A1:FC. '*' represents a '0.05' significance level with Bonferroni correction.

4.1.2 User Performance

Fig. 11 (a) and Fig. 12 (a) in Appendix C show overview summaries of user performance data for A1:FC.

Results from RM-ANOVAs did not find significant FRAME RATE×OBJECT SPEED interaction effect between for accuracy but found a significant main effect of FRAME RATE ($F_{3,93} = 4.427, p = 0.006, \eta_p^2 = 0.125$), and a significant main effect of OBJECT SPEED for accuracy ($F_{2.609,80.874} = 45.207, p < 0.001, \eta_p^2 = 0.593$). In terms of FRAME RATE, the accuracy in the 180fps condition ($M = 71.76, SD = 2.91$) was significantly higher than the 90fps condition ($M = 63.98, SD = 3.28; p = 0.005$). On the other hand, in terms of OBJECT SPEED, the accuracy in the 10m/s condition ($M = 80.98, SD = 2.19$) was significantly higher than in the other conditions ($p < 0.001$ for all three comparisons, 20m/s: $M = 66.641, SD = 2.34$, 30m/s: $M = 60.12, SD = 2.36$, 40m/s: $M = 61.15, SD = 3.07$). The accuracy in the 20m/s condition was significantly higher than in the 30m/s condition ($p < 0.001$).

We found a significant main effect of FRAME RATE ($F_{2.570,79.655} = 3.144, p = 0.037, \eta_p^2 = 0.092$) and a significant main effect of OBJECT SPEED ($F_{1.817,56.338} = 11.390, p < 0.001, \eta_p^2 = 0.269$) for reaction distance. On the contrary, the interaction effect for reaction distance was not significant ($F_{5.662,175.537} = 1.961, p = 0.078, \eta_p^2 = 0.059$). Post-

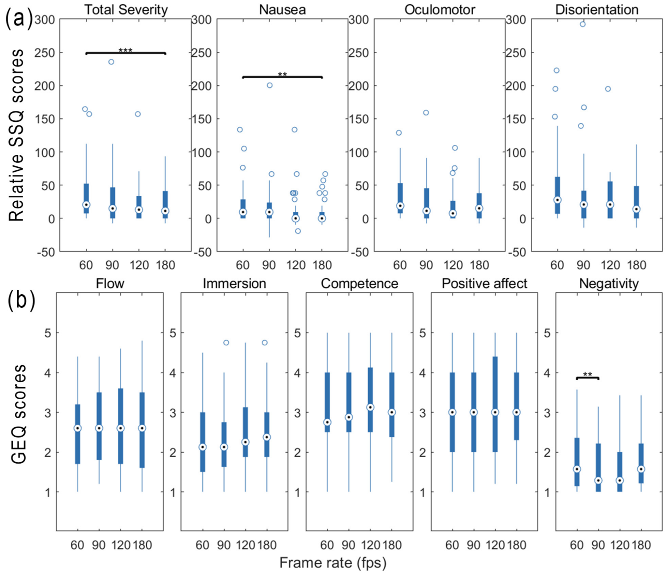

Fig. 8: Box plots of (a) the four relative SSQ sub-scores; and (b) the five GEQ sub-scores from A2:DV. '*' represents a '0.05' significance level with Bonferroni correction.

hoc analyses indicated that the reaction distance in the 90fps condition ($M = 0.85, SD = 0.07$) was significantly shorter than in the 60fps condition ($M = 1.02, SD = 0.07; p = 0.002$).

Similarly, we found a significant main effect of FRAME RATE ($F_{2.218,66.288} = 3.135, p = 0.047, \eta_p^2 = 0.092$) and a significant main effect of OBJECT SPEED ($F_{1.468,45.510} = 7.229, p = 0.004, \eta_p^2 = 0.189$) for effective reaction distance, but a significant interaction effect was not found ($F_{4.187,129.790} = 1.262, p = 0.288, \eta_p^2 = 0.039$). Post-hoc analyses indicated that the significant differences of effective reaction distance in terms of OBJECT SPEED are 20m/s ($M = 0.75, SD = 0.06$) $<$ 30m/s ($M = 0.87, SD = 0.09$) $<$ 40m/s ($M = 1.01, SD = 0.12$) (20m/s-30m/s: $p = 0.008$, 20m/s-40m/s: $p = 0.003$, 30m/s-40m/s: $p = 0.007$).

4.2 Application 2: Dynamic Vision Task

4.2.1 Subjective Measures

Fig. 8 shows a summary of the SSQ and GEQ data for A2:DV. The Friedman tests revealed statistically significant differences in Total Severity ($\chi^2(3) = 12.176, p = 0.007, W = 0.127$), Nausea ($\chi^2(3) = 14.926, p = 0.002, W = 0.155$), and Oculomotor ($\chi^2(3) = 9.901, p = 0.019, W = 0.103$) among the FRAME RATE conditions. Post-hoc tests showed significant differences between 180fps and 60fps in Total Severity ($Z = -3.233, p = 0.001$; 180fps: $Mdn = 11.22$, 60fps: $Mdn = 20.57$) and Nausea ($Z = -2.735, p = 0.006$; 180fps: $Mdn = 0$, 60fps: $Mdn = 9.54$) with 180fps having lower scores. We did not find significant differences in Disorientation ($p = 0.070$) among the different frame rates.

Results from the Friedman tests indicated statistically significant differences in competence scores ($\chi^2(3) = 9.586, p = 0.022, W = 0.100$) and negativity scores ($\chi^2(3) = 12.299, p = 0.006, W = 0.128$) among the frame rates. Significant differences were not found in the remaining factors ($p > 0.05$). Post-hoc tests showed negativity scores were significantly lower in the 60fps condition ($Mdn = 1.29$) than in the 90fps condition ($Mdn = 1.57; Z = -2.711, p = 0.007$). However, no significant differences were found in competence scores in the post-hoc tests.

4.2.2 User Performance

Fig. 11 (b) and Fig. 12 (b) in Appendix C show overview summaries of user performance for A2:DV.

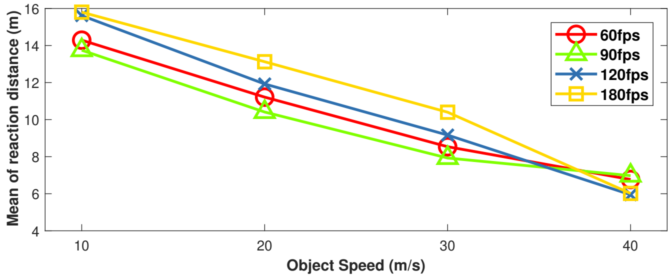

Fig. 9: Mean of reaction distance in A2:DV under 4 frame rates (60, 90, 120, and 180fps) and 4 object speeds (10, 20, 30, and 40). The results show a significant interaction effect of FRAME RATE×OBJECT SPEED on mean of reaction distance.

The main effect of OBJECT SPEED on accuracy is significant ($F_{1.288,39.936} = 17.605, p < 0.001, \eta_p^2 = 0.362$). Post-hoc tests showed that the accuracy difference of speed is 20m/s ($M = 98.20, SD = 0.65$) $>$ 30m/s ($M = 94.96, SD = 1.30$) $>$ 40m/s ($M = 88.16, SD = 2.47$) and 10m/s ($M = 99.53, SD = 0.17$) $>$ 30m/s $>$ 40m/s (10m/s-30m/s: $p = 0.001$, 10m/s-40m/s: $p < 0.001$, 20m/s-30m/s: $p = 0.002$, 20m/s-40m/s: $p < 0.001$, 30m/s-40m/s: $p < 0.001$). There were no other interaction or main effects on accuracy.

A significant interaction effect on reaction distance was found ($F_{4.364,135.273} = 2.552, p = 0.037, \eta_p^2 = 0.076$). Fig. 9 shows the means of reaction distance. As can be observed, the effect of FRAME RATE depends on the objects' speed for reaction distance. When moving at 20m/s, reaction distance was significantly affected by the frame rate ($F_{3,93} = 6.008, p = 0.001, \eta_p^2 = 0.162$). Post-hoc analyses indicated that the reaction distance in the 90fps condition was significantly shorter than in the 120fps ($p = 0.007$) and 180fps conditions ($p < 0.001$). Similarly, reaction distances were significantly affected by the frame rate when moving at 10m/s ($F_{3,93} = 2.866, p = 0.041, \eta_p^2 = 0.085$) and 30m/s ($F_{1.948,60.391} = 3.300, p = 0.045, \eta_p^2 = 0.096$). However, Post-hoc tests did not indicate any significant differences in the frame rate on reaction distance at 10m/s or 30m/s. On the other hand, at 40m/s, reaction distances were not significantly affected by the frame rate ($F_{1.887,58.486} = 1.146, p = 0.323$).

There was no significant interaction effect on effective reaction distance ($F_{3.114,96.546} = 2.062, p = 0.108, \eta_p^2 = 0.062$). The main effect of FRAME RATE on effective reaction distance was significant ($F_{3,93} = 6.830, p < 0.001, \eta_p^2 = 0.181$). Post-hoc analyses indicated that the effective reaction distance in the 90fps condition ($M = 9.09, SD = 0.74$) was significantly lower than in the 120fps and 180fps conditions ($p < 0.001$ for both cases; 120fps: $M = 10.26, SD = 0.83$, 180fps: $M = 11.05, SD = 0.93$). The main effect of OBJECT SPEED on effective reaction distance is significant ($F_{1.374,42.597} = 57.103, p < 0.001, \eta_p^2 = 0.648$). Post-hoc analysis indicates the significant differences of effective reaction distance in terms of OBJECT SPEED are 20m/s ($M = 11.53, SD = 0.97$) $>$ 30m/s ($M = 8.67, SD = 0.68$) $>$ 40m/s ($M = 5.31, SD = 0.31$) and 10m/s ($M = 14.89, SD = 1.32$) $>$ 30m/s $>$ 40m/s (10m/s-20m/s: $p < 0.001$, 10m/s-30m/s: $p < 0.001$, 10m/s-40m/s: $p < 0.001$, 20m/s-30m/s: $p < 0.001$, 20m/s-40m/s: $p < 0.001$, 30m/s-40m/s: $p < 0.001$).

4.2.3 Total Frame Fusion

As mentioned, we used TFF of the TEC displacement under both reaction distance and effective reaction distance (TFF under reaction distance and TFF under effective reaction distance for short) in A2:DV. Fig. 10 summarizes the means. The figure shows that the effect of frame rate depends on an object's moving speed for both measures (see also Fig. 11 (c) in Appendix C for a summary of the results).

A significant FRAME RATE×OBJECT SPEED interaction effect on TFF under reaction distance was found ($F_{6.863,212.765} = 2.804, p = 0.009, \eta_p^2 = 0.083$). When moving at 20m/s, TFF under reaction distances was significantly affected by frame rate ($F_{3,93} = 3.394, p =$

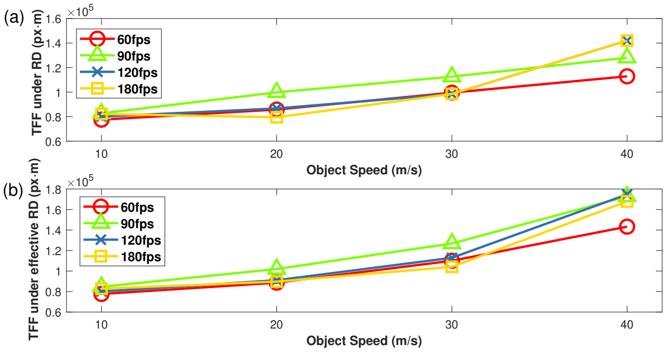

Fig. 10: (a) Means of TFF under reaction distance, and (b) Means of TFF under effective reaction distance in A2:DV under 4 frame rates (60, 90, 120, and 180fps) and 4 object speed (10, 20, 30, and 40m/s). RD denotes reaction distance. The results show significant interaction effects of FRAME RATE×OBJECT SPEED on both measures.

$0.021, \eta_p^2 = 0.099$). Post-hoc tests indicate the TFF under reaction distances differences in 180fps ($M = 79476.62, SD = 12802.54$) was significantly smaller than in 90fps condition ($M = 99811.34, SD = 12326.11; p = 0.007$). When moving at 40m/s, it was significantly affected by the frame rate ($F_{2.217,68.740} = 5.872, p = 0.003, \eta_p^2 = 0.159$). Post-hoc tests indicate the TFF under reaction distances differences in 60fps ($M = 112880.73, SD = 7951.82$) was significantly smaller than in 120fps condition ($M = 141943.50, SD = 8313.69; p < 0.001$) and 180fps condition ($M = 141950.56, SD = 8771.59; p = 0.001$). However, TFF under reaction distances was not significantly affected by the frame rate for objects moving at 10m/s ($p = 0.898$) and 30m/s ($p = 0.227$).

A significant FRAME RATE×OBJECT SPEED interaction effect on TFF under effective reaction distance was found ($F_{6.435,199.482} = 2.278, p = 0.034, \eta_p^2 = 0.068$). TFF under effective reaction distances were not significantly affected by frame rate when speed was 10m/s ($p = 0.818$), 20m/s ($p = 0.358$), and 30m/s ($p = 0.087$). When moving at 40m/s, it was significantly affected by the frame rate ($F_{3,93} = 8.729, p < 0.001, \eta_p^2 = 0.220$). Post-hoc tests indicate the TFF under effective reaction distances differences in 60fps ($M = 143282.47, SD = 8192.35$) condition was significantly smaller than in 90fps ($M = 172785.23, SD = 7150.35; p < 0.001$), 120fps ($M = 174699.27, SD = 8636.44; p < 0.001$), and 180fps ($M = 167839.58, SD = 10619.36; p = 0.002$) conditions.

4.3 General Feedback

After finishing all the conditions of the experiment for each participant, we conducted a semi-structured interview asking them about their general experience or other feelings about the two applications running at different frame rates and with objects at different speeds. Six participants said that lower frame rates made them feel more SS symptoms than higher rates. Eight participants said that higher rates helped them perform better. However, two participants (P1 and P25) mentioned that they did not believe that high rates were always better than lower frame rates. P1 said that the effect on the display with higher frame rates was at times too much to get used to it. P25 said that, although higher rates could bring a smoother experience, it could also lead him to have dizziness (that is, higher SS). Five participants said that they saw a very noticeable 'obvious' latency in 60fps and had to sometimes fill in (or 'imagine' as several participants describe the process) the gaps in the trajectory of the objects.

5 DISCUSSION

In terms of *subjective* measures, the SSQ data show that 120fps and 180fps caused significantly lower SS than 60fps for A1:FC and A2:DV, respectively. The GEQ data show that A2:DV using 60fps led to greater negativity than using 90fps. Both SSQ and GEQ data show that 60fps should not be used in VR to ensure a better experience with lower SS and fewer negative effects. If users want to have reduced SS, they would probably need to run their application at least 120fps, particularly for those VR scenarios that are similar to A1:FC. The GEQ data show no significant difference for other frame rates. Such results seem to indicate that there is no linear relationship on game experience among higher frame rates and lower frame rates. It shows that the effects of frame rate on game experience are more complicated compared to the effects on SS. According to the general feedback on game experience, a few participants did not like high frame rates due to individual differences. However, in general, the perceived differences from lower frame rates are more distinct. One reason could be that lower rates (60fps and 90fps) made a stronger impression on participants since they could more easily distinguish the visual differences between lower rates rather than higher rates (120fps and 180fps). This may have made participants pay more attention to lower rates when filling out the GEQ. In general, 120fps can still be regarded as an important lower threshold to support good user experience and still lead to low SS since there is no significant difference in game experience between 120fps and other rates, and 120fps and above can significantly cause less SS. In particular, after 120fps and 180fps, such benefits may become small and to a negligible extent for A1:FC and A2:DV, respectively. These findings answer parts of **RQ1** and **RQ2** (see Sect. 2.4).

In terms of *performance* measurements, the results from the first application (A1:FC) show that frame rate and object speed may contribute separately to how participants responded to the tasks. This is the main reason the above analysis did not show interaction effects but they point to significant effects of frame rate and object speed separately on participants' accuracy, reaction distance, and effective reaction distance. These results seem to indicate a greater impact of speed over refresh rate. To some extent, this is plausible as in this scenario participants learned that they did not have to pay much attention to the details of the fruits but if they focused on their movement and speed they could meet the task requirements. This observation was confirmed in the interviews when asked about the strategy for this scenario. Despite this, the results also point to significant effects of refresh rate on the performance metrics.

In the second application (A2:DV) which required users to pay more attention to the details of the objects, the reaction distance results indicate that when objects moving at 20m/s, participants could react to them significantly faster in 120fps and 180fps than in 90fps. Similarly, the effective reaction distance results show that participants could recognize the targets correctly at a shorter distance in 120fps and 180fps than 90fps. However, with objects at higher speeds in A2:DV, the results are not so clear cut because we did not find significant differences between 60fps and higher rates. To understand why, the new metric we developed, Total Frame Fusion (TFF), provides a possible explanation for this unexpected result.

TFF results under both reaction distance and effective reaction distance can help us understand how much information has been perceived by participants when they make decisions and make correct ones, respectively. Surprisingly, we found that, when an object moving fast at 40m/s, the TFF under reaction distance in 60fps was lower than in 120fps and 180fps. Moreover, with the same object's speed, the TFF under effective reaction distance in 60fps was lower than in other frame rate conditions, which were all higher than 60fps. The above results show that participants can distinguish the visual details with less visual information in 60fps for high-speed moving objects. At least five participants said that they felt an obvious latency at 60fps in the interview session. Therefore, one possible reason is that for such high-speed objects (e.g., at 40m/s), participants may have developed a strategy that was different from the one used in higher fps due to the relatively higher latency at 60fps. That is, participants seemed to make decisions before they got enough visual information (high TFF value) about the objects. As the results show, such a proactive strategy (compared to a more reactive one) allowed them to 'see' things clearly with even less visual information (small TFF value), as would have been the case at higher fps. In general, for high-speed objects, 60fps seemed to have forced participants to choose a different strategy compared to higher fps—one that seems to be a compensatory one. This can be regarded as evidence that frame rate and object speed can change users' reactive strategy into a more proactive one. The above results also show that TFF is a suitable objective metric for measuring the effect of frame rate on users' performance with dynamic objects in virtual environments.

In short, we found no definite, clear-cut threshold for user performance based on the four frame rate conditions (60, 90, 120, 180fps) since participants adjusted their strategy to compensate for the effect of low frame rate (at 60fps) to increase their performance. Insufficient visual information in 60fps can cause a different strategy with fast-moving objects (e.g., at 40m/s) than higher fps. These findings further answer **RQ1** and **RQ2** (see Sect. 2.4).

6 LESSONS GATHERED AND RECOMMENDATIONS

According to the above results, we distill the following recommendations for VR users and content developers.

- **R1**. For VR users who want to ensure a suitable VR experience with lower SS, they can consider choosing VR HMDs with 120Hz and above refresh rates. This is particularly relevant to environments with moving objects and users' attention to the objects' visual details is important to the task requirements.

- **R2**. VR users can choose VR HMDs with a high refresh rate to achieve a suitable level of performance and experience, especially when immersed in a VR application dealing with fast-moving objects. If the VR HMD does not support high refresh rates, users can choose to lower the speed of the objects or adjust other device features (like resolution) to allow them to see the details of such objects earlier.

- **R3**. For VR content developers, they should try to ensure that their VR content can run at 120fps or above and can be powered by a standard PC to ensure an adequate VR experience with low SS in virtual environments with moving objects and require players to pay attention to the objects' visual details. Moreover, if their VR content is targeted at competitive users (such as professional eSports or avid players), they should consider optimizing the VR content to have the highest possible frame rate to maximize performance and experience (including minimizing SS).

- **R4**. When designing environments with fast-moving objects but rendered at low frame rates, designers may want to investigate the provision of supporting features to help users adapt their behavior in a way that will not negatively affect their experience.

7 LIMITATIONS AND FUTURE WORK

This work has some limitations, which can serve as directions for future work. As explained earlier, we chose the Pimax 5K Super because it has the highest refresh rate (180Hz) among all available VR HMDs according to Fig. 1 (b). However, it does not support eye trackers. When eye tracking capabilities are available in HMDs that support both high resolution and frame rate, we plan to extend this work to include eye gaze/movement data to better understand the effect of different frame rates on users' experience and behavior based on the nature of the task at hand and virtual objects' properties they have to interact with. Moreover, our 60fps condition that run on a 90Hz display may suffer from screen tearing—a visual artifact from multiple frames in a single screen draw due to a lack of synchronization between frame rate and refresh rate. We will test a 60fps condition under a 60Hz display or apply vertical synchronization when newly deployed products allow us to do so in the future.

In this study, we focus on the evaluation of user performance on dynamic objects with different speeds under different frame rates since better dynamic vision on dynamic objects is one of the main benefits of frame rates. As a first exploration of the topic, we used controlled tasks we developed to test the effect of frame rate because commercial games or applications may have elements that we cannot control and could become unwanted confounding factors. In the future, we plan to test the effect of frame rate in more types of VR scenarios with multiple or complex tasks, such as first-person shooter games or racing games [7, 25, 26, 32, 36, 37], to validate our current results in more general VR environments. Moreover, we had the object speeds grow in complexity to reduce participants' workloads because pilot trial participants stated that it was not easy to hit fast-moving targets. Such a fixed order may induce learning effects but is also in line with how users play games (i.e., moving from easy tasks initially to more difficult tasks gradually). In the future, it will be helpful to have a condition where the object speed is randomized to mitigate any learning effect. This could possibly take place after participants have had some prior extended exposure to the tasks and environment. Although we recommend 120fps as an overall lower threshold, a more precise threshold may exist between 90fps and 120fps. To determine a more precise threshold, we plan to explore other fps conditions between 90fps and 120fps in the future.

We fixed the resolution in all conditions at 2560×1440 per eye. The main reason for having a constant resolution is that this research does not focus on the HMDs' resolution but on their refresh rate. Also, the 2K resolution is chosen because a recent work has shown that this resolution leads to an enhanced user experience in VR HMDs, particularly in games, without affecting users' performance and increasing their SS levels [37]. As such, this choice would ensure that any negative effect on user experience and performance is not due to resolution issues. In the future, when higher-resolution HMDs that can also run at high refresh rates are available, we plan to revisit this work and see if the same findings hold and to find further insights into the effect and trade-offs between high resolution and refresh rate on users' experience and performance.

Given the limited research and available measurements for quantifying how much visual information is perceived by users when dealing with moving objects in VR environments, our aim to introduce TFF is to have some standard quantitative metric that researchers can use. Our results show its potential as a metric to allow comparative assessments across resolution conditions. In the future, we plan to improve and extend it for comparing other factors (e.g., resolution). Moreover, a more general TFF means that it can be used to measure visual information in complex experiments so that for example a three-factor (TASK×FRAME RATE×OBJECT SPEED) experiment is possible.

8 CONCLUSION

In this paper, we presented the results of a user study and analysis of the effects of frame rate on user experience, performance, and simulator sickness (SS) in virtual reality (VR) applications. We evaluated user experience and performance under 4 different frame rates (60, 90, 120, and 180fps) in two controlled VR applications. We found that 120fps is an important lower threshold for VR applications with moving objects. 120fps and higher rates can make users feel lower SS symptoms without negatively affecting their overall experience. In general, 120-180fps or above seems more suitable if users want (or are expected) to perform better in VR environments when visual accuracy and reaction speed are important and when dealing with moving objects. In addition, we introduced a new metric, Total Frame Fusion (TFF), for measuring users' received visual information when focusing on moving objects. We showed that it could be used for evaluating user performance on dynamic objects under specific speed and frame rate conditions. We found that in 60fps, insufficient visual information could make users change their strategy to rely more on their prediction based on limited perceived visual information compared to higher rates in some cases (especially for objects with high speed such as 40m/s).

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A VR HMD FRAME RATE SETTING IN UNITY3D

To change the frame rate of VR of an HMD in Unity3D, we temporarily removed the VR frame rate lock by setting the graphics API from DX11 to Vulkan in editor mode in Unity3D (see `https://docs.unity3d.com/Manual/GraphicsAPIs.html`). We then used the NVIDIA control panel to limit the maximum frame rate to 60fps under a 90Hz driver setting (see `https://www.nvidia.com/en-us/drivers/control-panel/`). These steps allowed us to build a 60fps condition accurately.

B ABBREVIATIONS AND ACRONYMS USED

VR: Virtual Reality	HMD: Head-Mounted Display	fps: frames per minute
A1:FC: Application 1 (Fruit Cutting Task)	A2:DV: Application 2 (Dynamic Vision Task)	SS: Simulator Sickness
SSQ: Simulator Sickness Questionnaire	GEQ: Game Experience Questionnaire	TEC: Tumbling E Chart
TFF: Total Frame Fusion	ROI: Region of Interest	RD: reaction distance
ROI_P: the size of a rectangular ROI in pixels	$ROI_{\%}$: alternative notation of ROI_P in % format	px: pixel

Table 1: Abbreviations and acronyms used

C ADDITIONAL FIGURES

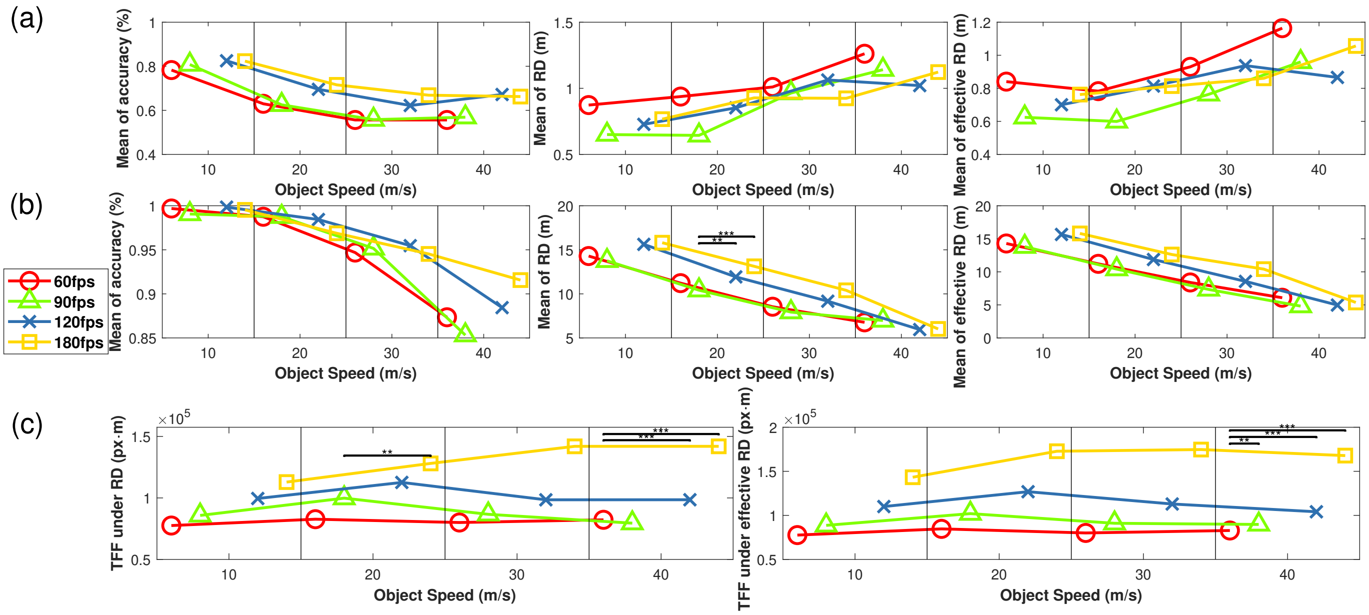

Fig. 11: Summary of interaction effects in user performance. (a) Application 1: Fruit Cutting Task; and (b) to (c) Application 2: Dynamic Vision Task. RD denotes reaction distance. An offset is added to the lines (labeled with '*', which represents a Bonferroni-adjusted significant difference at a '0.05' level).

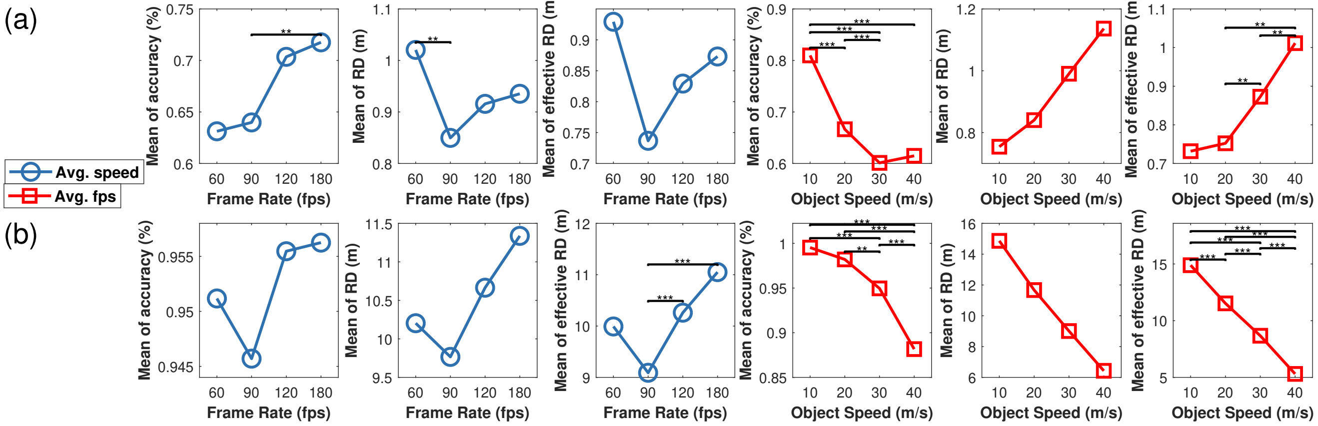

Fig. 12: Summary of main effects in user performance (on average speed and average fps). (a) Application 1: Fruit Cutting Task, and (b) Application 2: Dynamic Vision Task. RD denotes reaction distance. '*' represents a Bonferroni-adjusted significant difference at a '0.05' level.