Influence of Temporal Delay and Display Update Rate in an Augmented Reality Application Scenario

Ming Li
RWTH Aachen University
Aachen, Germany
mingli@cs.rwth-aachen.de

Katrin Arning
RWTH Aachen University
Aachen, Germany
arning@comm.rwth-aachen.de

Luisa Vervier
RWTH Aachen University
Aachen, Germany
vervier@comm.rwth-aachen.de

Martina Ziefle
RWTH Aachen University
Aachen, Germany
ziefle@comm.rwth-aachen.de

Leif Kobbelt
RWTH Aachen University
Aachen, Germany
kobbelt@cs.rwth-aachen.de

ABSTRACT
In mobile augmented reality (AR) applications, highly complex computing tasks such as position tracking and 3D rendering compete for limited processing resources. This leads to unavoidable system latency in the form of temporal delay and reduced display update rates. In this paper we present a user study on the influence of these system parameters in an AR point‘n’click scenario. Our experiment was conducted in a lab environment to collect quantitative data (user performance as well as user perceived ease of use). We can show that temporal delay and update rate both affect user performance and experience but that users are much more sensitive to longer temporal delay than to lower update rates. Moreover, we found that the effects of temporal delay and update rate are not independent as with longer temporal delay, changing update rates tend to have less impact on the ease of use. Furthermore, in some cases user performance can actually increase when reducing the update rate in order to make it compatible to the latency. Our findings indicate that in the development of mobile AR applications, more emphasis should be put on delay reduction than on update rate improvement and that increasing the update rate does not necessarily improve user performance and experience if the temporal delay is significantly higher than the update interval.

CCS Concepts
•**Human-centered computing → User studies;** •**Computing methodologies → Mixed / augmented reality; Perception;**

MUM '15, November 30-December 02, 2015, Linz, Austria

DOI: http://dx.doi.org/10.1145/2836041.2836070

Author Keywords
mobile augmented reality, point‘n’click, latency, temporal delay, display update rate, user study, perception tolerance, ease of use.

INTRODUCTION
Augmented reality (AR) is an emerging technology that enables digitally enhanced views of real objects [23]. By using camera and/or sensors in a smart device, AR allows to project layers of different digital information - textual information, videos, and photos - directly on real world items. The concept of AR requires that the digital virtual objects are seamlessly embedded into the surrounding environment so that users perceive them as real. In practice, we observe that this AR illusion often breaks down due to system latency [28] such as temporal delay and low display update rates. Additionally, the impact of these system parameters on the users' experience and perception varies in different AR scenarios [14]. As shown in Figure 1, in an AR system the temporal delay of object tracking could change during the run time, due to different technical reasons. When it is shorter than the display refresh interval, it is masked by the display update period. Therefore, the effective system latency that users may perceive is dominated by the display update rate. When it is longer than the refresh interval, users actually notice a "system lag" as the virtual object is drifting away from the position where it should be in the real world. This system lag can be perceived as more or less relevant out of the perspective of the user in terms of affective valence and arousal [2]. In dynamic situations in which the information of the digitally enhanced view is time-critical, the latency can be irritating if not fatal. In other situations in which the digital information is less vital, the latency can be perceived as bothersome (worst case) or acceptable (best case). Therefore, the combination of temporal delay and update rate can decisively influence user acceptance of an AR system.

Although the measurement of AR system latency has been investigated before [28, 29], considering user perceptions in AR application scenarios, the impact to corresponding user

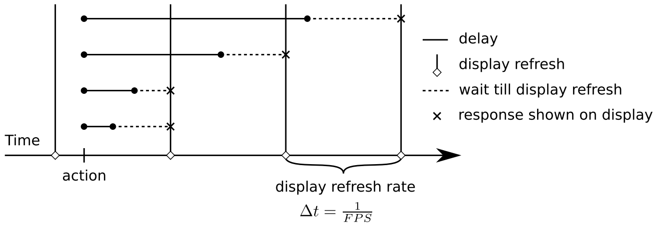

Figure 1. Relation between delay and display update rate. In an AR system, the temporal delay can vary, either shorter or longer than the duration of one display refresh.

perception has not been fully covered. First, it is not yet understood which combination of temporal delay and update rate, both contributing to the system latency, is most detrimental to user performance. Second, it is not clear whether the system latency-induced performance decrease is in line with user experience, i.e., comparable decrease in user experience with increasing system latency. Third, as the meaningfulness of noticeable system latency in real life may differ depending on the seriousness and urgency of the situation, an evaluation of acceptance or decline of using the AR application needs to be explored.

In this paper, we present a formal study on users' perception of the influence of temporal delay and display update rate in an AR point'n'click game scenario. Our goal is to explore the change of user performance and experience under different temporal delay and update rate levels so that we can understand which system latency aspect impacts users' acceptance of an AR application the most. The development of future AR systems can benefit from our findings in that they can serve as a development guideline to allocate computation or communication resources. For example, if increasing the display update rate cannot necessarily improve user experience (e.g., because the system delay is too large), we can limit the update rate and shift the unused processing resources to other important tasks like improving graphical rendering quality. To collect our data, we conducted an experiment based on a point'n'click game, "duck shooting", in a controlled environment. The point'n'click task was chosen as it is not only a highly reliable experimental task in these contexts [3], but it also reflects an ecologically valid task which frequently occurs in natural, real life environments [11, 19]. This paper is organized as follows: We survey some previous research work in the next section. Then the implementation of the duck shooting game is presented, followed by the design of our user study. Furthermore, the experiment results are shown and we discuss our findings and implications.

RELATED WORK

There are many potential sources for system latency in a real-time video see-through AR application. Some of them are due to the hardware (CCD and other sensor readout, memory access) and some emerge from the necessity to load balance several compute intensive software modules such as visual tracking and 3D rendering. In this paper, we investigate the influence of system latency in the form of temporal delay and low display update rates in a black box fashion and do not consider which system component actually caused it. In virtual reality (VR) scenarios, the influence of temporal delay and update rate has been investigated previously. Allison et al. [1] reported effects of system latency and head motion on perceptual stability of the VR environment. Ware and Balakrishnan [34] presented a study of object selecting behavior in a VR environment with head and hand tracking system in which the lag of hand tracking was reported to be more critical to users' performance. In the field of AR, some researchers investigated the influence of system latency in special AR scenarios [18, 14]. For example, Knorlein et al. [14] tested the influence of visual and haptic delays on stiffness perception in a medical education application. However, in different AR scenarios, the users' subjective sensitivity to system latency varies a lot. In an AR navigation scenario, delay of signals could result in disorientation while in a point'n'click scenario it could reduce the users' accuracy of selection. In this paper, we explore the impact of system latency to user experience in an AR point'n'click scenario, an aspect, which has not been reported before. The AR point'n'click scenario has been used by some researchers [25, 26] who called it magic lenses interaction. Their works focus on validating Fitts' law in 3D AR scenarios, therefore the system latency factor is not taken into account. From a human factors point of view, the question about user behavior and tolerance towards system response times in human-computer interaction (HCI) has been studied predominately in working context [32, 6, 7]. Comprising the key results, long system response times are perceived as annoying, aggravating, and bothersome [5, 15] and can even lead to severe, physiologically detectable stress reactions [27]. It was found that the specific task type, the task difficulty level, and the time delay were the major factors that determine delay tolerance [33]. Negative effects of system response times have been examined across a wide range of computer tasks, e.g., tele-text [31], voice mail [6], video streaming [13], watchability of videos [9], video conferencing [36], and even in special professional areas, e.g., tele-surgery [30, 10], or even professional mechanics in the context of maintenance and repair [12]. Whenever system response time is predictable, performance as well as user experience are less negatively affected [27, 35]. However, so far there is no adequate knowledge of how strongly users might react on variations of temporal delay and update rate in AR scenarios. In particular, it is not yet understood which of the two technical factors, is more decisive for the performance and the tolerated degree of deterioration users are willing to accept.

SYSTEM IMPLEMENTATION

In order to evaluate the influence of temporal delay and update rate in an AR point'n'click scenario, we implemented a duck shooting game in a lab environment (Figure 2 bottom).

The system consists of three components: an IR tracking system, a set of markers, and a mobile AR interface. Our AR setup is powerful enough to provide almost ideal conditions (temporal delay $\leq$ 10 ms, update rate 60 Hz). We use this as a baseline reference and add artificial temporal delays and reduce the frame rate for our experimental conditions. The temporal delay in a realistic AR system consists of: (1) camera input (converting optical signals to image data that can be

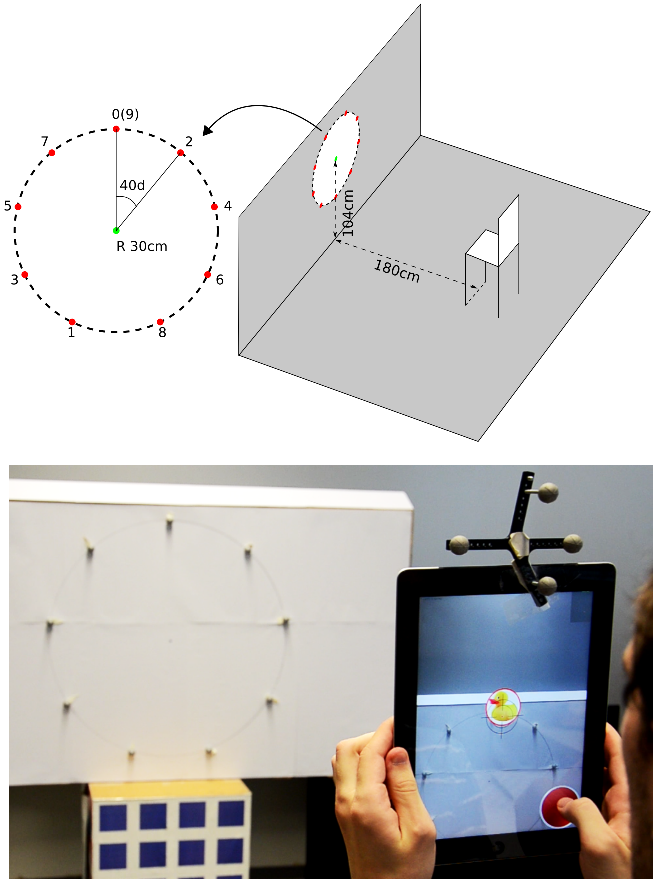

Figure 2. Duck shooting game setup: Top-Left: 9 markers on the plane; Top-Right: The setup of the marker plane and the user's position (chair). Bottom: a photo shows the setup from a user's perspective.

further processed); (2) visual registration (detecting targets from the image data, providing its 2D/3D position); (3) display update (rendering 3D objects at the target position).

If the visual registration is computed remotely, e.g., on a remote server, a network round-trip time needs to be included as well. In the presented experiment, we use the IR tracking system to simulate the visual tracking process in an AR system in which camera input + visual registration are replaced by a constant location update (60 Hz) via WLAN (stable network latency in a lab environment). Therefore, the overall temporal delay is controlled by artificially changing tracking delay and display update, the two independent variables in our study.

IR Tracking System

In our implementation, we use an infra red tracking system (ARTTRACK System [4]). It provides a 60 Hz tracking update rate and 6 degrees of freedom (DOF). The detected position and orientation information are streamed to a mobile tablet device via a local WLAN. Note, we do not choose other visual tracking methods like 2D marker-based tracking, because the infra red tracking system provides a higher update rate and gives us more flexibility for the latency and update rate testing.

Figure 3. The Point'N'Click interface of the duck shooting game.

Setup of Markers

As target objects, nine markers are placed on a vertical flat surface, arranged in a circle with a fixed angle difference between each other (40 degree) (see Figure 2), in front of the user. A calibrated marker set is attached to the mobile device, providing position and orientation information of the device. The information of the detected markers (3 DOF, static positions in this scenario) and the marker set (6 DOF) is sent to the mobile interface to update visualization.

Mobile AR Interface

The game user interface (UI) runs on a third generation iPad. It consists of a live video input, augmented objects, and a game UI (Figure 3). The video input shows the environment using the back camera. For the augmented object (the target), we render a virtual duck billboard in the tracking system's world space, overlaying on a chosen marker position. The game UI has a crosshair for aiming and a trigger button for shooting.

For each trial of the game, a user has to shoot successively 19 ducks (2 loops of 9 markers plus 1 starting duck to focus the user on the starting point). Each time, only one duck appears. Ducks are displayed in a diagonal-clockwise sequence [25] to provide a replicable localization of the single duck positions (Figure 2, top left). The starting position of a sequence is randomly selected. Users have to aim at the virtual duck with the crosshair center and press the trigger button to shoot. A gunshot sound effect is played when the trigger is pressed. The hit point is computed by color picking at the crosshair center. Once the duck is hit, a short animation (the duck icon flipping) is displayed to give the user feedback. After the animation, the next duck in the sequence appears.

QUESTIONS ADDRESSED AND LOGIC OF EXPERIMENT

In an experimental approach, we contrast temporal delay and display update rate. Both modulations might have an impact on the users' perception. The questions guiding this research are the following:

1. What is the critical technical combination of temporal delay and update rate that is still acceptable for users?
2. Do individual performance measurements and users' perceived ease of use deviate from each other?

The motivation for this research is to derive guidelines for AR application developers to improve system performance so that the impact on user performance and ease of use is maximized.

METHOD

In a game-like experimental setting, participants were asked to shoot virtual ducks in different settings using a tablet computer. Temporal delay and update rate were technically varied while performance and ease of use were assessed. In order to understand users' perceptions of varied delays in the AR application, a quantitative methodology was chosen. Therefore, we compiled a questionnaire that had to be answered after each trial (assessing ease of use and user experience, respectively).

Independent Variables

In the context of AR point'n'click application scenarios, two independent variables were examined: **temporal delay** and **display update rate**. The **temporal delay** denotes the time interval between a user's action and the system's response. From a user's perspective, the temporal delay describes an interval between the action of moving the device and seeing the game interface react. Two different temporal delays are chosen: The low delay condition lasts 100 ms and the high delay condition 200 ms. We selected these two levels because 100 ms is a well-known temporal threshold for human perception [20]. While at 200 ms, the delay can be perceived clearly.

The second independent variable is the **display update rate**. This variable indicates the number of frame updates per second (FPS or Hz). The higher the refresh rate, the more fluent the display will appear. Accordingly, a low refresh rate will produce hard jittering, similar to a stop-motion. Two update rates were chosen: a low update rate with 10 Hz and a high update rate with 20 Hz. These two levels were selected, because they cover an important FPS range in interactive graphical applications in which below 10 Hz is treated as noticeably low frame rate and above 20 Hz is considered fluent [8, 21]. Both independent variables were combined as a matching pair in all variations possible. Overall, four different experimental conditions were tested:

1. delay 100 ms / update rate 10 Hz
2. delay 100 ms / update rate 20 Hz
3. delay 200 ms / update rate 10 Hz
4. delay 200 ms / update rate 20 Hz.

The overall purpose of the presented study is to focus on a delay x update range that can potentially benefit AR development the most. Once such a range is discovered, we can have denser samples within that range in a future study.

Dependent Variables

Three different dependent groups of variables are chosen which reflect the objective performance and subjective ease of use of the participants, respectively.

Performance

Four different measures are taken: *Completion time* is measured in seconds in order to assess the reaction time users needed to fulfil a point'n'click task. *Number of shots* indicates the accuracy of shooting. It describes the number of shots taken to hit successive targets in one round. *Moving distance* of the tablet (measured in mm), assessed as the total distance of translation of the tablet while fulfilling a task. *Rotating angle* (measured in degree), assessed as the total angle of rotation of the tablet while fulfilling a task. The moving distance and rotating angle can tell us how much a user needs to move the tablet in order to hit a target, which reflects the efficiency of aiming in the AR point'n'click scenario. A longer travel distance or a larger rotating angle mean that a task requires more effort in aiming the target.

Ease of Use

In order to measure ease of use, participants rated the perceived ease of use after each condition (temporal delay x update rate combination). To understand the nature of the deterioration, which might be caused by temporal delay and update rate combination, we assessed different facets of the ease of use during task completion. The following items had to be rated on a 6-point Likert-scale: do not agree at all (1) to totally agree (6): The trial was easy to accomplish; Aiming was easy; Hitting was easy; Change of position between ducks was easy; Jittering of the duck was disruptive.

Study design

The study design followed a 2 (temporal delay) x 2 (update rate) plan with repeated measurements. A within subject design was used, i.e., each participant went through a baseline condition first and then four conditions of temporal delay and update rate combinations. The order of the later four conditions was balanced across participants to avoid order effects. Note that the baseline was always applied first (as an anchor) in order to frame a common reference condition for all participants. The baseline condition was assembled without any artificial temporal delay and with a display update rate of 60 Hz. All participants were informed explicitly that the baseline is a reference condition in which no deterioration is given. After the baseline condition, the four trials were carried out one after another. Within each trial, participants had to hit 19 ducks using a tablet device. Completion time, number of shots, moving distance and rotation angle recording started with the successful shooting of the first duck. Each of the five trials (1 + 4) lasted about 3.5 minutes. After each trial, there was a short questionnaire to be answered in which participants rated the ease of use in the respective condition and could meanwhile also recover from possible fatigue. Each questionnaire took about 4 minutes. After all trials, an overall questionnaire was answered which included items about demographic data, handling the device, ease of use, as well as user characteristics. The overall duration of each experiment was about 40 minutes for each participant.

Procedure

The participants were instructed to take a seat in front of the vertical flat surface, hold the tablet in front of their upper body, and use its display to aim (point) and fire (click). First, a short tutorial was given, explaining to the participants the usage of the tablet as a duck-shooting device in terms of a point'n'click task (crosshair aiming and trigger button). Participants were instructed to pace the single trials independently and to work as fast and as accurately as possible. However, they were not explicitly informed about the different temporal delay x update rate conditions, but the purpose of the study (to explore which technical quality mode is acceptable for users) was generally introduced. Prior to starting the experimental trials, each participant was asked to finish a training trial (19 target ducks) to familiarize them with the interface and the task. The training trial used the same settings as the baseline trial, i.e., no extra temporal delay was added to the practice trial and the display rate was 60 Hz. The training trial was excluded from the data analysis. After the training trial, participants started the actual tests (the 5 trials described before).

Participants

29 participants took part in the study with an age average of 24.5 years (SD = 4). 45% of the sample were female, 55% male. The participants were mostly university students (of both technical and social disciplines). Participants were not remunerated for their efforts but fulfilled a university course requirement. Overall, the motivation to take part was high as participants were keen to see novel AR-applications in a game context. 21% of the participants stated they played computer games twice a week whereas 38% reported to almost never play computer games and thus do not bring any computer game experience. 40% of the participants reported to be familiar with the meaning of AR. The participants' experience with AR applications was quite mixed. Only 14% of the participants indicated frequent use of AR applications. In contrast, the majority reported to never or only sometimes use AR applications.

RESULTS

Data was processed by analyses of variance for repeated measurements for the performance data (post-hoc comparisons were done with Fisher's LSD tests). Regarding user ratings, non-parametric Friedman analyses were run. The level of significance was set at $\alpha = 0.05$. First, we report on the outcomes regarding the main effects of update rate and temporal delay in the performance variables (completion time, number of shots, moving distance, and rotating angle). For calculating the main effect of delay (100 vs. 200 ms), data of the different update conditions were aggregated; for the main effect of update rate (10 vs. 20 Hz), data were aggregated across delay conditions. Also, we analyzed the four different delay x update rate conditions against the baseline. Furthermore, outcomes regarding the ease of use measures are reported.

Performance

First, we calculated the main effects of temporal delay and update rate on dependent variables. In a second step, all five conditions are contrasted (Table 1 shows an overview of all descriptive variables).

For the Completion Time, significant main effects of temporal delay ($F(2,27) = 160.4; p < .05$) as well as update rate ($F(2,27) = 158.9; p < .05$) were found. Delay leads to a significant increase in completion time (baseline: $M = 23.7s$ $SD = 4.7$); delay 100ms: $M = 29.9s$ ($SD = 4.2$); delay 200ms: $M = 38.9s$ ($SD = 6.9$), with significant differences between

Table 1. Overview of means (M) and standard deviations (SD) of experimental conditions. Baseline condition (0ms 60 Hz). CT: completion time in second; Shot: number of shots (higher value indicates worse accuracy); Dist: moving distance in millimeter (lower value means less movement in aiming); Ang: rotating angle in degree (lower value indicates less rotating action in aiming).

		CT.	Shot.	Dist.	Ang.
Baseline	*M*.	23.78	20.34	2310.63	367.91
	SD.	4.66	2.04	750.61	53.34
100ms 10Hz	*M*.	30.81	22.10	2415.49	386.16
	SD.	4.88	4.53	718.81	51.24
100ms 20Hz	*M*.	29.02	24.00	2469.15	407.21
	SD.	3.96	5.64	789.44	52.67
200ms 10Hz	*M*.	38.37	28.93	2786.96	453.19
	SD.	7.63	10.64	720.08	79.62
200ms 20Hz	*M*.	39.53	34.20	3249.82	519.04
	SD.	9.33	18.83	1523.01	183.55

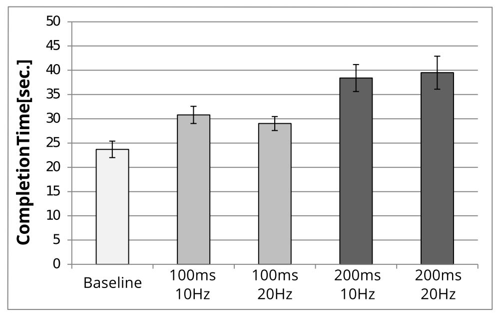

Figure 4. Mean completion time (in second) depending on the delay conditions and update rates. 5% confidence interval is included. Lower value indicates faster completion time.

all three variations). Also, when looking at the update rates, a significant increase of time can be revealed in comparison to the baseline. In Figure 4, outcomes of all combinations of update rates and temporal delay as well as the baseline are visualized.

Post-hoc tests showed that the baseline is significantly superior to all other combinations, which also differed significantly from each other. In addition, the effect of different update rates under the same delay condition was computed, i.e., comparing 100ms/10Hz to 100ms/20Hz and 200ms/10Hz to 200ms/20Hz. A significant effect of update rate was found between 100ms/10Hz and 100ms/20Hz ($t(28) = 3.2; p < .004$). In 100ms delay condition, a lower update rate leads to a significant increase in completion time (100ms/10Hz: $M = 30.8s$ ($SD = 4.9$); 100ms/20Hz: $M = 29.0s$ ($SD = 4.0$)). No significant effect was discovered between 200ms/10Hz and 200ms/20Hz.

Regarding Number of shots, a similar picture emerged. Significant main effects of delay ($F(2,27) = 10.8; p < .05$) and of update rate ($F(2,27) = 11.2; p < .05$) were revealed. The number of shots increased significantly with increasing delay (baseline: $M = 20.3$ ($SD = 2$); delay 100ms: $M = 23.1$ ($SD = 4.7$); delay 200ms: $M = 31.6$ ($SD = 13.7$)) as well as with increasing update rates (baseline: $M = 20.34$ ($SD = 2.3$); update 10 Hz: $M = 25.5$ ($SD = 6.9$); update 20 Hz: $M = 29.1$

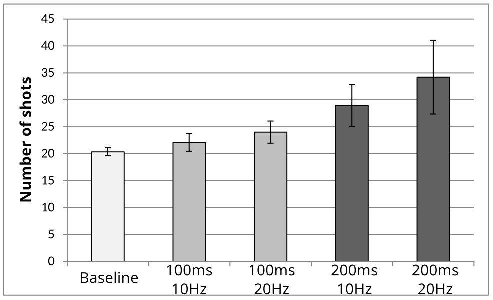

Figure 5. Mean number of shots depending on the delay conditions and update rates. 5% confidence interval is included. Lower value indicates better accuracy.

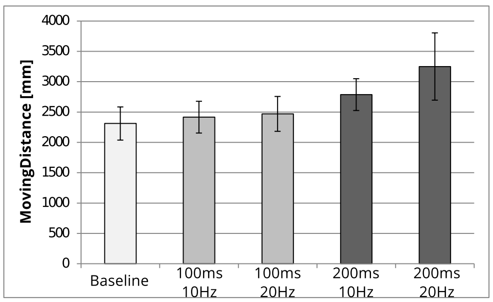

Figure 6. Mean moving distance (mm) depending on the delay conditions and update rates. 5% confidence interval is included. Lower value means less movement in aiming.

($SD = 11.2$)). In Figure 5, outcomes for all four delay x update combinations are pictured in comparison to the baseline.

According to LSD post-hoc tests, all five conditions differed significantly from each other. When we looked into the effect of update rate under the same delay, significant effects between 100ms/10Hz and 100ms/20Hz ($t(28) = 2.59; p < .02$) as well as between 200ms/10Hz and 200ms/20Hz ($t(28) = 2.11; p < .04$) were found. Higher update rates lead to a higher number of shots (100ms/10Hz: $M = 22.1$ ($SD = 4.5$); 100ms/20Hz: $M = 24.0$ ($SD = 5.6$); 200ms/10Hz: $M = 28.9$ ($SD = 10.6$); 200ms/20Hz: $M = 34.2$ ($SD = 18.8$)).

As a third performance measure, the Moving Distance was surveyed. In line with speed and accuracy, the moving distance was significantly affected by the delay ($F(2,27) = 19.9; p < .05$) and the update rate ($F(2,27) = 20.1; p < .05$). For the baseline, a mean moving distance of $M = 2310.6mm$ ($SD = 750mm$) was measured. With increasing delay, moving distance increased accordingly (delay 100ms: $M = 2442.4mm$ ($SD = 735.5.2$); delay 200ms: $M = 3018.4mm$ ($SD = 1008$)). The same holds true for increasing update rates (update 10 Hz: $M = 2601.2mm$ ($SD = 697.5$); update 20 Hz: $M = 2859.5mm$ ($SD = 1092.4$)). Descriptive data of the five combinations of update and delay variations can be taken from Figure 6.

Comparing different update rates within the same delay, no significant effect was found between 100ms/10Hz and 100ms/20Hz. Between 200ms/10Hz and 200ms/20Hz, it missed the significance level ($t(28) = 2.0; p = .06$).

Finally, among the performance measures, we assessed the Rotating Angles of mobile devices when targeting the ducks.

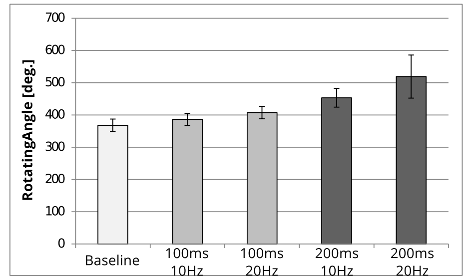

Figure 7. Mean rotating angle (deg) depending on the delay conditions and update rates. 5% confidence interval is included. Lower value indicates less rotating action in aiming.

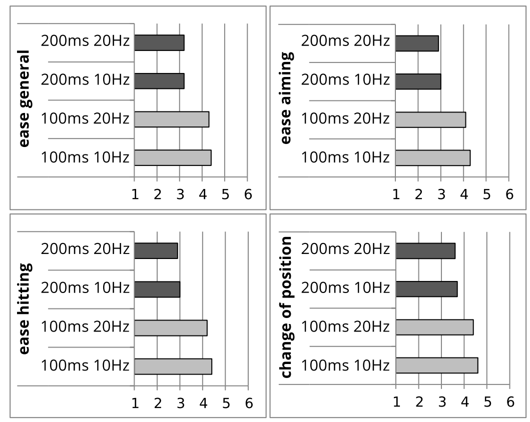

Figure 8. Ease of use ratings. Upper left: general ease of the trial; upper right: Ease of aiming; lower left: Ease of hitting and lower right: change of position of the duck. High values indicate better ease of use (6 = max).

Significant main effects of delay ($F(2,27) = 40.7; p < .05$) and update rates ($F(2,27) = 46.3; p < .05$) were found. In contrast to the baseline ($M = 367.9deg$; $SD = 53.3$), a delay of 100 ms increased the rotating angles to $M = 396.7deg$ ($SD = 49.6$) and even $486.1deg$ ($SD = 114.3$) in the 200ms delay condition. When contrasting all experimental conditions (baseline, delay 100 ms, delay 200 ms as well as update rates 10 or 20 Hz), again all conditions differed significantly from each other (LSD post-hoc tests). Figure 7 shows the results.

Considering the effects of update rate under the same delay, significant effects between 100ms/10Hz and 100ms/20Hz ($t(28) = 3.6; p < .001$), as well as between 200ms/10Hz and 200ms/20Hz ($t(28) = 2.1; p < .04$) were found. Higher update rates lead to more rotation (100ms/10Hz: $M = 386.2deg$ ($SD = 51.2$); 100ms/20Hz: $M = 407.2deg$ ($SD = 52.7$); 200ms/10Hz: $M = 453.2deg$ ($SD = 79.6$); 200ms/20Hz: $M = 519deg$ ($SD = 183.6$)).

Ease of Use

Beyond performance, which yielded significant effects of temporal delay and update rates, it is of major interest if and to which extent ease of use and acceptance are deteriorated by both technical factors. Figure 8 shows the rating outcomes. The perceived ease of shooting the ducks varies across conditions. Noteworthy, however, is that the delay does decrease the perceived ease to a much higher extent than the update rate. Statistical testing (Friedman rank analysis) revealed that conditions differ significantly from each other (general ease: $X2 = 27.7$ ($df = 3$); $p < 0.05$; aiming: $X2 = 28.8$ ($df = 3$); $p < 0.05$; hitting: $X2 = 38.1$ ($df = 3$); $p < 0.05$; change of position $X2 = 16.6$ ($df = 3$); $p < 0.05$). Comparing the effects of different update rates in the same delay condition (100ms/10Hz to 100ms/20hz and 200ms/10Hz to 200ms/20Hz), Wilcoxon's paired rank analysis did not show significant results.

DISCUSSION

This study examined the impact of varied temporal delay and display update rates on users' performance and ease of use. Taking the underlying questions into account, we can conclude the following:

The changes of delay and update rate are noticeable to users. Higher update rates do not necessarily improve the user's performance.

The data portrays that the changes of temporal delay and update rate are noticeable to users and influence their performance and experience significantly. Objective performance data is more discriminative and allows us to distinguish between the two different temporal delay and update rate conditions. With respect to performance measures, higher delay does significantly deteriorate the speed and accuracy of point'n'click performance. For a fixed delay, increasing the update rate does not necessarily improve user performance. On the contrary, higher update rates can even decrease user performance if the delay is longer than the update interval. In this case, the higher the display update rate is, the more target "drifting" (or "jumping") will appear to the user. For example, if we compare 100ms/20Hz and 100ms/10Hz, 20 Hz corresponds to a 50 ms frame interval and 100 ms delay means the position updates every 2 frames. Therefore, when the display gets updated (the video input layer refreshes), the virtual object still remains in the old screen position (thus desynchronized from the environment). From the user perspective the virtual object seems separated from the real environment and the AR illusion breaks. For a 10 Hz (lower) update rate, although the display is updated only every 100 ms, it is synchronized with the target position update. From the user's perspective, although the screen update is less fluent, the virtual object is at least moving together with the real environment thus maintaining the AR illusion.

Users are more tolerant of the change of update rate than the change of delay. As for perceived ease of use, people are more tolerant regarding update rate changes under a fixed delay. While performance and ease of use are generally positively correlated, objective performance measurement differs from user subjective acceptance in one specific aspect: While the performance data shows a significant difference between a fixed delay and a changing update rate throughout, the users' perceived ease of use does not vary for changes in update rates but rather remains constant. A shorter delay irrespective of the update rate always leads to a higher acceptance. Thus, update rates do not have a strong impact on users' perception, at least in the tested range between 10Hz and 20Hz. Therefore, system performance optimization efforts should rather focus on reducing delay, e.g., by utilizing local sensors/computing, or shifting computing capacities to other critical tasks, e.g., to improve rendering quality instead of frame rate.

Some final remarks deal with potential limitations with respect to methodological aspects and the generalizability of our findings.

User group, a first limitation refers to the selection of a young and technology-experienced group of potential mobile phone users who do not represent the whole group of mobile device users. As mobile device usage is increasingly an essential requirement for older adults, it should be examined in how far effects of temporal delay and update rates might affect their perception and performance too. On the one hand, one could expect that these effects play only a minor role as information processing is less sensitive at older age; on the other hand, however, the experience of a delayed response of a mobile device could be still considered as more bothersome by seniors.

Regarding *experimental setting*, in order to segregate the influence of update rate and temporal delay on performance and user perception in a first approach, we focused on selected combinations of both technical variables. They were chosen based on human reaction model [20], which do not fully represent the latency in the state-of-the-art AR applications. For a more detailed picture of users' behaviors when being confronted with current technical limitations, lower latencies [22] and a finer graduation of combinations should be pursued.

Another aspect directs to *target characteristics*. In this study, we used solely static targets in a 2D plane. However, it is important to learn how temporal delay and update rates will affect performance and ease of use in a dynamic setting [17], e.g., using animated figures and a 3D environment, in which more user movement is required and in which simulator sickness could play a critical role [24].

Finally, from a methodological point of view, the item 'user experience' should be considered in a broader sense. In this research, ease of use and user experience were measured according to several dimensions related to the task completion procedure. Though, still, user experience comprises many more aspects that are relevant in such AR applications. According to Qualinet [16], a white paper on definitions of Quality of Experience, a complex model of user experience is proposed in which context and system factors, (technical) source signals, and human factors are comprised. Further studies will look into the perceptual nature of the relation between AR system quality and user experience.

CONCLUSION

In this paper, we presented a user study on the influence of temporal delay and display update rate to users' performance and experience in an AR point'n'click scenario. Different combinations of temporal delay and update rate were experimentally evaluated for an AR duck shooting game in a lab environment. Our results show that both temporal delay and update rate impact user performance and experience significantly. However, user perception is more tolerant to update rate than temporal delay. A design guideline for future AR applications can thus be as follows: To technically improve the user experience of an AR system, the major effort should focus on reducing temporal delay, e.g., by improving target tracking. In case that the temporal delay can not be further reduced, it is unnecessary to keep increasing the display update rate if the temporal delay is longer than one refresh interval. Thus, processing resources can be shifted to improve other parts of the system, e.g., graphical quality.

ACKNOWLEDGMENT

This work was supported by the UMIC Research Centre, RWTH Aachen University.

REFERENCES

1. Robert S. Allison, Laurence R. Harris, Michael Jenkin, Urszula Jasiobedzka, and James E. Zacher. 2001. Tolerance of Temporal Delay in Virtual Environments. In *Proceedings of the Virtual Reality 2001 Conference (VR'01) (VR '01)*. IEEE Computer Society, Washington, DC, USA, 247–. http://dl.acm.org/citation.cfm?id=580521.835823
2. Alessandro Angrilli, Paolo Cherubini, Antonella Pavese, and Sara Manfredini. 1997. The influence of affective factors on time perception. *Perception & Psychophysics* 59, 6 (1997), 972–982. DOI: http://dx.doi.org/10.3758/BF03205512
3. C. Armbrüster, C. Sutter, and M. Ziefle. 2007. Notebook input devices put to the age test: The usability of trackpoint'n'click and touchpad for middle-aged adults. *Ergonomics* 50, 3 (2007), 426–445.
4. ART. 2014. ARTTRACK System. (2014). http://www.ar-tracking.com.
5. Raymond E. Barber and Henry C. Lucas, Jr. 1983. System Response Time Operator Productivity, and Job Satisfaction. *Commun. ACM* 26, 11 (Nov. 1983), 972–986. DOI:http://dx.doi.org/10.1145/182.358464
6. B.S. Caldwell and P. Paradkar. 1995. Factors affecting user tolerance for voice mail message transmission delays. *International Journal of Human-Computer Interaction* 7 (1995), 235–248. doi: 10.1080/10447319 509526123.
7. B.S. Caldwell and E. Wang. 2009. Delays and user performance in human-computer-network interaction tasks. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 51 (2009), 813–830. doi: 10.1177/0018720809359349.
8. Stuart K. Card, Allen Newell, and Thomas P. Moran. 1983. *The Psychology of Human-Computer Interaction*. L. Erlbaum Associates Inc., Hillsdale, NJ, USA.
9. J. Y.C. Chen and J. E. Thropp. 2007. Review of Low Frame Rate Effects on Human Performance. *Trans. Sys. Man Cyber. Part A* 37, 6 (Nov. 2007), 1063–1076. DOI: http://dx.doi.org/10.1109/TSMCA.2007.904779
10. M.D. Fabrizio, B.R. Lee, D.Y. Chan, D. Stoianovici, T.W. Jarrett, C. Yang, and L. R. Kavoussi. 2000. Effect of time delay on surgical performance during telesurgical manipulation. *Journal of Endourology* 14, 2 (2000), 133–138.
11. Tovi Grossman and Ravin Balakrishnan. 2004. Pointing at Trivariate Targets in 3D Environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*. ACM, New York, NY, USA, 447–454. DOI: http://dx.doi.org/10.1145/985692.985749
12. S. Henderson and S. Feiner. 2011. Exploring the Benefits of Augmented Reality Documentation for Maintenance and Repair. *Visualization and Computer Graphics, IEEE Transactions on* 17, 10 (Oct 2011), 1355–1368. DOI: http://dx.doi.org/10.1109/TVCG.2010.245
13. Ngo Quang Minh Khiem, Guntur Ravindra, and Wei Tsang Ooi. 2011. Towards Understanding User Tolerance to Network Latency in Zoomable Video Streaming. In *Proceedings of the 19th ACM International Conference on Multimedia (MM '11)*. ACM, New York, NY, USA, 977–980. DOI: http://dx.doi.org/10.1145/2072298.2071917
14. B. Knorlein, M. Di Luca, and M. Harders. 2009. Influence of Visual and Haptic Delays on Stiffness Perception in Augmented Reality. In *Proceedings of the 2009 8th IEEE International Symposium on Mixed and Augmented Reality (ISMAR '09)*. IEEE Computer Society, Washington, DC, USA, 49–52. DOI: http://dx.doi.org/10.1109/ISMAR.2009.5336501
15. W. Kuhmann, W. Boucsein, F. Schaefer, and J. Alexander. 1987. Experimental investigation of psycho-physio-logical stress-reactions induced by different system response times in human-computer interaction. *Ergonomics* 30 (1987), 933–943.
16. P. Le Callet, S. Möller, and A. Perkis. 2012. Qualinet white paper on definitions of quality of experience. *European Network on Quality of Experience in Multimedia Systems and Services (COST Action IC 1003).* (2012).
17. V. Lippi, C.A Avizzano, D. Mottet, and E. Ruffaldi. 2010. Effect of delay on dynamic targets tracking performance and behavior in virtual environment. In *RO-MAN, 2010 IEEE*. 446–451. DOI: http://dx.doi.org/10.1109/ROMAN.2010.5598607
18. M.A Livingston and Zhuming Ai. 2008. The effect of registration error on tracking distant augmented objects. In *Mixed and Augmented Reality, 2008. ISMAR 2008. 7th IEEE/ACM International Symposium on*. 77–86. DOI: http://dx.doi.org/10.1109/ISMAR.2008.4637329
19. I. Scott MacKenzie. 1992. Fitts' Law As a Research and Design Tool in Human-computer Interaction. *Hum.-Comput. Interact.* 7, 1 (March 1992), 91–139. DOI: http://dx.doi.org/10.1207/s15327051hci0701_3
20. Robert B. Miller. 1968. Response Time in Man-computer Conversational Transactions. In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I (AFIPS '68 (Fall, part I))*. ACM, New York, NY, USA, 267–277. DOI: http://dx.doi.org/10.1145/1476589.1476628

21. A. Newell and S. K. Card. 1985. The prospects for psychological science in human-computer interaction. *Human-computer interaction* 1, 3 (1985), 209–242.

22. MIT News. 2014. In the blink of an eye. (2014). http://news.mit.edu/2014/in-the-blink-of-an-eye-0116.

23. W. Pasman, A. van der Schaaf, R. L. Lagendijk, and F. W. Jansen. 1999. Accurate overlaying for mobile augmented reality. *Computers & Graphics* 23, 6 (1999), 875–881.

24. H. Renkewitz and T. Alexander. 2007. Perceptual Issues of Augmented and Virtual Environments. *FGAN-FKIE WACHTBERG (GERMANY)* (2007).

25. Michael Rohs and Antti Oulasvirta. 2008. Target Acquisition with Camera Phones when Used As Magic Lenses. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 1409–1418. DOI: http://dx.doi.org/10.1145/1357054.1357275

26. Michael Rohs, Antti Oulasvirta, and Tiia Suomalainen. 2011. Interaction with Magic Lenses: Real-world Validation of a Fitts' Law Model. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2725–2728. DOI: http://dx.doi.org/10.1145/1978942.1979343

27. F. Schaefer. 1990. The effect of system response times on temporal predicatability of work flow in HCI. *Human Performance* 3 (1990), 173–176.

28. T. Sielhorst, Wu Sa, A Khamene, F. Sauer, and N. Navab. 2007. Measurement of absolute latency for video see through augmented reality. In *Mixed and Augmented Reality, 2007. ISMAR 2007. 6th IEEE and ACM International Symposium on*. 215–220. DOI: http://dx.doi.org/10.1109/ISMAR.2007.4538850

29. Colin Swindells, John C. Dill, and Kellogg S. Booth. 2000. System Lag Tests for Augmented and Virtual Environments. In *Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technology (UIST '00)*. ACM, New York, NY, USA, 161–170. DOI: http://dx.doi.org/10.1145/354401.354444

30. J.M. Thompson, M.P. Ottensmeyer, and T.B. Sheridan. 1999. Human factors in telesurgery: effects of time delay and asynchrony in video and control feedback with local manipulative assistance. *Telemedicine Journal* 5, 2 (1999), 129–137.

31. Thum M., Boucsein W., Kuhmann W., and Ray W.J. 1995. Standardized task strain and system response times in human-computer interaction. *Ergonomics* 38 (1995), 1342–1351.

32. W.C. Treurniet, P.J. Hearty, and M.A. Planas. 1985. Viewers' responses to delays in simulated teletext reception. *Behaviour and Information Technology* 4 (1985), 177–188.

33. E. Wang. 2002. User's Delay Perception and Tolerance in Human-Computer Interaction. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 46 (Sept. 2002), 651–655. doi:10.1177/154193120204600511.

34. Colin Ware and Ravin Balakrishnan. 1994. Reaching for Objects in VR Displays: Lag and Frame Rate. *ACM Trans. Comput.-Hum. Interact.* 1, 4 (Dec. 1994), 331–356. DOI:http://dx.doi.org/10.1145/198425.198426

35. F. Weber, C. Haering, and R. Thomaschke. 2013. Improving the Human-Computer Dialogue With Increased Temporal Predictability. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 55, 5 (2013), 881–892.

36. J. Xu and B. W. Wah. 2013. Exploiting just-noticeable difference of delays for improving quality of experience in video conferencing. *the 4th ACM Multimedia Systems Conference* (Feb. 2013), 238–248.