Effects of Lower Frame Rates in a Remote Tower Environment

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Abstract— **In the field of aviation, "Remote Tower" is a current and fast-growing concept offering cost-efficient Air Traffic Services (ATS) for aerodromes. In its basics it relies on optical camera sensor, whose video images are relayed from the aerodrome to an ATS facility situated anywhere, to be displayed on a video panorama to provide ATS independent on the out-of-the-tower-window view. Bandwidth, often limited and costly, plays a crucial role in such a cost-efficient system. Reducing the Frame Rate (FR, expressed in fps) of the relayed video stream is one parameter to save bandwidth, but at the cost of video quality. Therefore, the present article evaluates how much FR can be reduced without compromising operational performance and human factor issues. In our study, seven Air Traffic Control Officers watched real air traffic videos, recorded by the Remote Tower field test platform at the German Aerospace Center (DLR e.V.) at Braunschweig-Wolfsburg Airport (BWE). In a passive shadow mode, they executed ATS relevant tasks in four different FR conditions (2 fps, 5 fps, 10 fps & 15 fps) to objectively measure their visual detection performance and subjectively assess their current physiological state and their perceived video quality and system operability. Study results have shown that by reducing the FR, neither the visual detection performance nor physiological state is impaired. Only the perceived video quality and the perceived system operability drop by reducing FR to 2 fps. The findings of this study will help to better adjust video parameters in bandwidth limited applications in general, and in particular to alleviate large scale deployment of Remote Towers in a safe and cost-efficient way.**

Keywords-Remote Tower; air traffic control; low frame rate; video update rate; detection performance; physiological stress; perceived video quality; perceived system operability.

I. INTRODUCTION

According to several authors, operating regional airports in Germany [29] or elsewhere, e.g., in Australia [4], is already outdated due to high financial deficits. However, a promising alternative, called Remote Tower, invented in 2005 at German Aerospace Center (DLR e.V.) in Braunschweig [13] [14] is already on its way. The main idea consists in enabling ATS decoupled from the Out-of-The-Window (OTW) view from a conventional aerodrome tower. Video cameras capture the aerodrome scenery and relay the video stream to an ATS facility where it is displayed on a video panorama presentation. The new ATS facility can still be located at the Tower building but actually is independent on that location and can be sited anywhere. The gained advantages are manifold. Cameras can provide additional view points of the aerodrome, supplementary infrared cameras can look through fog or darkness or new augmentation features improve the former OTW view, which contributes to safety. Costly constructions of new Towers or maintenance of existing Tower buildings can be saved. The core idea, however, is that more than one aerodrome can be connected to this remote ATS facility. A so called Remote Tower Center (RTC) has the advantage that the ATCOs can switch between aerodromes or can provide ATS to more than one aerodrome simultaneously providing their service when and where it is actually needed. As a main effect, their working time would be exploited much more efficiently [15] and, as a side effect, human errors due to underutilization at work would be diminished [40].

In 2015 the first RTC went in operation. Swedish ATCOs control air traffic of Sundsvall and Örnsköldvik airport from the RTC in Sundsvall [35]. Despite this first success, ambitions to improve the Remote Tower concept run high. Thus, new modalities for controlling a pan-tilt-zoom camera [16] or to augment the video panorama vision [17] are developed and adapted to various operational needs dependent on the operational context. For instance, an ATCO without any approach radar support would need a very high video resolution to detect traffic at far distances. Instead, an ATCO who controls traffic movements on the aerodrome maneuvering area would probably need a sufficient Frame Rate (FR) to precisely judge about the velocity of the traffic. In fact, both, resolution and FR are important operational quality parameter but also bandwidth consuming parameters and therefore cost-driving factors in Remote Towers systems. Thus, new Remote Tower implementations aim to optimize these parameters to a better benefit-cost ratio. With this in mind, we focus on the effects of reduced FR in a Remote Tower context. Certainly, FRs below the critical flicker frequency (CFF) could contribute to a perceived loss of movement fluidity, which might result in perceived loss of video quality. But does lower FRs also evoke negative effects, such as reduced ability to detect traffic movements on the displayed video panorama or even cause physiological stress in ATCOs and lower system operability?

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This paper addresses therefore the following research question: What are the effects of lower FRs in a Remote Tower environment on:

1) Visual detection performance,
2) Physiological stress,
3) Perceived video quality,
4) Perceived System operability?

The paper is structured in the following parts: Section II aims at presenting theoretical background concerning the perception of movement, distortions that can appear during video transmissions and a review of scientific literature about the impact of low frame rates on the operator. Linking these three aspects together allows us to specify the research question and the hypotheses. Section III explains the chosen methods and the procedure of the study. Then, in Section IV we will present the obtained results in descriptive and inferential statistics. In Section V these results will be explained and discussed based on theoretical findings and the research question. Section VI draws explicit conclusions by illustrating how the results of the conducted study contribute to science and future Remote Tower implementations.

II. THEORETHICAL BACKGROUND

A. *Motion perception*

In order to understand better the meaning of reduced FR for humans, we will firstly explain the importance for human beings to perceive motion and, secondly, explain how fluid motion is perceived by humans.

1) *Importance of motion perception for human beings*

The perception of moving objects is a phenomenon that humans take for granted. In fact, since the earliest childhood, a baby's attention is guided towards moving objects [26]. According to [33], motion perception permits humans to anticipate what he calls "collision time" to estimate the velocity of stimuli. Furthermore, he suggests that the utility of perceiving motion leads to perceiving objects in a tridimensional environment. Other reasons that underline the importance of motion perception consist in distinguishing a stimulus from its background and understanding different textures of objects [33]. For instance, if a gray airplane is in front of a gray cloud, it might be difficult to distinguish the flying object from its background. A light penetration from a different angle can be perceived when the plane moves. In conclusion, we can state that motion perception permits the observer to get to know more about the details of the environment s/he's in. In order to understand to which extent a movement appears to be fluid, some basics of psychophysics and cinematography are necessary and will be explained in the following section.

2) *Fluid motion perception*

In psychophysics, psychologists refer to absolute threshold if the minimal intensity necessary to perceive a stimulus is perceived by 50% of the observers [21]. As in [39], the CFF is described as the frequency at which the flickering of a flash is not distinguishable from a constant light source. In reality, this threshold can vary by the luminosity of the discontinuous light [21]. According to [24], the sensibility of CFF can also depend on the contrast between the stimulus and its environment. Therefore, the human eye is more sensible to temporal frequencies in high contrast situations between 15 and 20 Hz. The idea of a CFF is also used in cinematography. In cinematographic history, 13 presented images per second were identified as being critical for creating the sensation of fluid movement [23]. Concerning the first movies, 16 frames per second (fps) were not sufficient for showing fluid movements because of the visually perceived intermittent time between each frame. Therefore, cinematographs found a solution by showing the same image two or three times in a successive manner. In total, this means a presentation of 32 or 48 images per second [23] from which 16 are different. More precisely, movies were presented at 16 fps with a refresh rate of 32 Hz or 48 Hz. It's important not to confuse these two notions. Nowadays, the regular FR in cinemas and TV is either 24 fps or 30 fps [23]. FR and refresh rate are two important notions to understand the meaning of human perception of fluid movements in virtual environments. However, perceived fluidity of movements is not the only factor that contributes to an almost perfect presentation of the outer world when it comes to cinematography. Therefore, the next section will treat distortions likely to appear during tele transmissions.

B. *Reality distortions through tele transmission*

Despite the similarities between an optical sensor camera and the human eye, no camera can represent what we see with our proper eyes. Perceiving the world around us in a stereoscopic manner is already a limit for most conventional cameras that render a monoscopic image. Further, image resolution plays an indispensable role [2]. It allows us to perceive objects from a far distance in a detailed manner. The higher the image resolution, the better we can discriminate stimuli at bigger distances. The human eye has a visual acuity of ca. 1 arc minute [25]. In other words, from a distance of 1 km, the human eye can discriminate two points with a distance of 28 cm. However, conventional Remote Tower camera systems dispose of a medium image resolution [36] lower than 1 arc minute. With 2 arc minutes for instance, a camera could only discriminate two pixels with a distance of 56 cm from a distance of 1 km.

Latency or lag can be another distortion appearing in real-time tele-transmission systems caused by different sources (e.g., transmission problems, data conversion problems). They are expressed by a temporal delay between the input of information into a system and the output as a presentation of the information to the operator [5]. When we face different latency times in between of the presented frames, we talk about jitter.

Finally, the presented FR can result in a distortion of reality. By its reduction, the fluid perception of the movement drops as well. As we have seen it in the previous section, 13 fps are judged as being necessary in order to

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perceive fluid movement. This estimation is not absolutely correct, since the threshold can vary between several parameters, for instance the radial velocity of the perceived object. Another distortion related to FR refers to frequency interferences [2], like the well-known wagon-wheel-effect. In a Remote Tower environment, this effect can appear wherever periodic movements are faced, e.g., rotor blades of an aircraft or blinking lights. Some blinking lights need time to light up and are only at their maximum of luminance for a few instants. Hence, by reducing FR, the probability to capture an image during the maximum of luminosity diminishes as well. This could be critical particularly at night or low visibility.

C. Review of low FR effects on the operator

Limited bandwidth made several concerned parties study impacts of low FR on operators [7] [36] [38]. Due to high data transmission costs, researchers have investigated several parameters in order to reduce bandwidth. In the next section, we will present studies that focus on the effects of low FR on performance, psycho-physiological health of operators, as well as on perceived video quality.

1) Effects of low FR on operator visual detection performance

In the context of a Remote Tower environment, in a research study DLR investigated effects of low FR in a real-time tower simulation scenario: 6 fps, 12 fps and 24 fps were tested in order to evaluate the performance of ATCOs to visually discriminate and predict in real-time if aircraft after touchdown is in danger of a runway overrun due to low braking. Then, they were asked about how sure they were about their answer. Results show that by reducing FR, the level of certitude decreases. Further, the authors recommend a FR greater than 30 to achieve a maximum visual discriminability for dynamic events [10] [18]. Another study about unmanned ground vehicles and aircraft showed that the performance of detecting obstacles does not decrease by reducing the FR from 30 fps to 5 fps [7]. Reference [20] obtains similar results in a study about target detection in a 2 fps and 25 fps condition. By reducing FR, the participants' performance did not change in a significant manner. Thus, divergent results can be found. One possible explanation is that not only FR is a factor affecting performance. By a meta-analysis on existing studies in the field of effects of low FRs on performance [6] it was concluded that the effect of low FR on performance of participants is above all task-dependent. Moreover, they have identified an interaction of FR with image resolution. The authors suggest that the right balance between FR and image resolution can help to perceive depth accurately and hence increase the perception of movement in the areas that are farer away from the observer. They also suggest that performance depends on the participants' characteristics, too.

Thus, experienced participants in virtual environments might be less affected by FR reduction. However, not only performance is an important factor to consider when reducing FR. The operator's well-being is an essential parameter to study before lower FRs can be applied. Therefore, the next section will treat impacts of low FRs on psycho-physiological health of operators.

2) Effects of low FR on psycho-physiological health of operators

Regarding to psycho-physiological health, the effects of low FR have been evaluated very rarely. Reference [7] refers to a study at which they tested physiological stress in terms of cyber sickness about several unmanned ground vehicles and aircraft in different FR conditions. The used questionnaire (Simulator Sickness Questionnaire, SSQ) has been validated within a sample of 4000 pilots who participated in trainings in different flight simulators [27]. Nowadays, the SSQ is also used for evaluating cyber sickness in other virtual environments [28]. In study [7] the effects of low FR were non-significant. Thus, participants did not feel sicker in a simulation at 5 fps than at 30 fps. Another study [9] tested spatial stability in a virtual environment by varying the FR (6 fps, 12 fps & 20 fps). As a result, more participants felt sick by reducing FR. Reference [20] did not find significant results. Even though participants at 2 fps expressed higher workload and frustration, the expressed psycho-physiological stress was not significantly higher than at 25 fps. Furthermore, adverse health effects associated with low FRs do not appear in the occupational disease lists [3]. Taking into account these outcomes, divergent results can be found again.

3) Effects of low FR on perceived video quality

In scientific literature, we found several studies evaluating perceived video quality in different FR conditions. The perceived quality is often evaluated from acceptability and personal preference. In the context of a study concerning the performance in first person ego shooters, a study varied FR (3 fps, 7 fps, 15 fps, 30 fps & 60 fps) and image resolution (320x240 pixels, 512x384 pixels & 640x480 pixels) [8]. The results clearly indicate a significant preference for higher FRs and even more for a higher image resolution. Surprising effects have been found in a study that aimed to evaluate the video quality under different FR conditions (6 fps, 10 fps, 12 fps, 15 fps, 18 fps, 20 fps & 24 fps) and two image resolution conditions (low & high). A significant difference of video acceptability was not found between different FRs. Moreover, participants preferred higher image resolution to higher FRs [32]. In a study testing the video acceptability in different FR conditions (5 fps, 10 fps & 15 fps), it was stated that video acceptability decreases by reducing FR [1]. In reference [31] the type of motion is stressed: *"The type of motion in a sequence was important when considering the effects of FR on subjective quality"*.

To conclude, it is difficult again to find an appropriate FR threshold to guarantee the spectator's satisfaction in terms of video quality. As the previous studies already have suggested, it is very likely that not only FR plays a determinant role for acceptance of video quality.

4) *Effects of low FR on the perceived operability*

Until now, we have presented studies that examined effects of lower FR on performance, operator health and perceived video quality. However, these three parameters seem to be insufficient to evaluate if a Remote Tower system can be operated in a safe and efficient manner. If the user is not convinced of the system operability, errors can emerge by expressed mistrust in the system. According to [30], confidence in a system and emerging risks can play a mediator role in the system reliability. A system can seem to be perfect but is not if the user does not have a good feeling about it.

D. *Research question*

The general aim shared by all Remote Tower actors is to develop a system that allows remote air traffic control in the best cost-efficient ratio. Regarding this aim, a known limit is bandwidth. Nowadays, data transmission is still expensive and can be a financial threat if resources are not used efficiently. According to [2], crucial factors concerning bandwidth are field of view, image resolution, color depth, FR and data compression, which seem to be widely accepted, but opinions diverge largely when it comes to image resolution and FR. Some stakeholders believe that higher FR is preferable to higher image resolution. In fact, they believe that low FRs can decrease performance and operator health. However, so far there is no scientific proof that justifies these two presumptions. As it has already been expressed in the theoretical part, effects of low FRs on performance are likely to be task dependent [6] and do not give us clear information about operator health. Yet, impact of low FRs in Remote Tower environments has never been thoroughly tested with an experimental design. On the basis of context analysis and preexisting scientific literature, we will now propose six hypotheses.

E. *Hypotheses*

$H_{1,1}$: By reducing the FR from 15 fps to 10 fps, 5 fps or 2 fps, the adequate assessment of moving objects by ATCOs decreases.

$H_{0,2}$: By reducing the FR from 15 fps to 10 fps, 5 fps and 2 fps, the operator's performance in visual detection tasks will not decrease.

$H_{0,3}$: ATCOs' performance in visual tracking tasks does not decrease significantly by reducing the FR from 15 fps to 10 fps, 5 fps or 2 fps.

$H_{0,4}$: The physiological stress of operators does not increase significantly when FR is reduced from 15 fps to 10 fps, 5 fps or 2 fps.

$H_{1,5}$: The ATCOs' perception of the video quality will decrease when the FR is reduced from 15 fps to 10 fps, 5 fps or 2 fps.

$H_{1,6}$ The ATCOs' perceived system's operability will decrease when the FR is reduced from 15 fps to 10 fps, 5fps or 2 fps.

III. METHODS

A. *Tested variables*

The independent categorical variable corresponds to the chosen FR that will be presented in a video at four modalities: 2 fps, 5 fps, 10 fps, and 15 fps. Concerning the dependent variables, the first is to measure the participants' visual performance in three different dimensions: "Adequate Assessment of Moving Objects" (AAMO), "Visual Detection Tasks" (VDT) and "Visual Tracking Tasks" (VTT). The second dependent variable evaluates the participants' "physiological stress", the third one the ATCOs' "perceived video quality", and the fourth one the ATCOs' "perceived operability of the low FR system".

B. *Participants*

Seven male ATCOs between 31 and 58 years (M = 41.7, SD = 12.0) and five pseudo ATCOs (four men, one woman) between 26 and 52 years (M = 44.0, SD = 10.42) took part in the experiment. Their nationalities were German, English, Hungarian, Norwegian, Romanian and Swedish. We chose pseudo ATCOs as a non-expert control group in order to control potential motivational bias concerning physiological stress. ATCOs were directly invited by an invitation letter. All ATCOs and pseudo-ATCOs were familiar with the Remote Tower concept.

C. *Preparation of the study equipment*

1) *Video material collection, selection and edition*

For the experiment the DLR Remote Tower field test platform at Braunschweig-Wolfsburg Airport (BWE) was used. Fig. 1 shows the camera sensors on the roof of the DLR building surveying BWE aerodrome (left). On the right hand side the ATCO working position is depicted. The research prototype is operated with 2 arc minute image resolution and a FR of 30 fps.

Several hours of audio and video material have been recorded via the platform, assessed and selected. Firstly, only records which complied with EUROCAE [12] standard test conditions were selected. Further, it was checked for broad traffic diversity and other relevant visual occurrences (e.g., flock of birds). This step was supported by four ATCOs. In a third step, the final 30-fps video stream was computed to four content-identical streams with 2 fps, 5 fps, 10 fps and 15 fps and a length of 80 minutes each. 2, 5, 10 and 15 fps were chosen as 30 fps is a multiple of them, which helps to avoid the maximum of jitter. 2 fps as the lowest FR was chosen since this FR corresponds to the minimum standard of FR tolerated in a Remote Tower environment [12]. To complete the construction, the video material had to synchronize with the external sound and the radio transmissions. Finally, the jitter was measured in each experimental condition to ensure that it lies below the maximum tolerated value of 0.5 seconds [19].

Figure 1. DLR Remote Tower field test platform at Braunschweig-Wolfsburg Airport (BWE) (left: Camera sensors; right: ATCO working position).

2) Construction of the mid-run visual performance evaluation grid

In a first step, we chronologically listed events that refer to ATC relevant visual tasks, and associated them with the visual requirements stated by the interviewed ATCOs and those in the requirements for EUROCAE Remote Tower specifications [12]. These events were divided into three different categories of questions: the AAMO, VDT, and VTT. As for the AAMO, we mainly took into account the ATCOs' fears of not being able to properly assess the velocity or the stimulus' movement direction. Thus, an exemplary task is to evaluate whether a flashing light can be perceived in a safe and efficient manner. Other tasks include the assessment of flying birds' direction, wind direction and movements of aircraft propellers and human beings on the aerodrome. An exemplary task for VDT consists in detecting an aircraft in the final approach area or in the traffic pattern as soon as possible. Perceiving an aircraft in those positions represents visual requirements according to the interviewed ATCOs. Regarding VTT, the instruction consists in following an aircraft during the take-off phase and hitting a buzzer when it was not noticeable anymore. After classifying all possible tasks, we created and selected a list of possible questions that follows the chronology of occurrences.

3) Construction of the post-run questionnaire

In order to measure the physiological stress of the participants, we concentrated on mentioned symptoms in the interview, such as fatigue, nausea, headache, eye strain or dizziness, which are consistent with the items in a SSQ questionnaire to evaluate cyber sickness [27]. It contains 16 items and the scale is divided into three subscales which measure the dimensions "Nausea", "Oculomotor" and "Disorientation".

The second part of the post-run questionnaire consists in rating the perceived video quality and the perceived operability on a 7-point Likert scale.

4) Pretest

A pseudo-ATCO and two ATCOs participated in the pretest to verify that the scenario did not contain inconsistencies that the tasks relate to an ATCO's daily routine, and that the questionnaires are comprehensible. They accepted the setting and confirmed that the number of tasks was enough not to be bored and that the variety of tasks corresponds well to the different visual requirements that ATCOs have to face during their daily work.

D. Experimental Procedure

The study took place between May 15th 2017 and June 12th 2017. The procedure of the study was structured in two parts. The briefing phase represented the part in which ATCOs were informed and prepared for the actual experiment. The experimental phase corresponded to the video session and the completion of the post-run questionnaire. The written and spoken language was English. The participants were informed that they will see the same video four times at four different FRs. They were left unaware of the FRs to be tested in order to avoid potential effects of previously formed attitudes. They were explained that the order of the videos was randomized for methodological reasons and that they had to complete the SSQ questionnaire before the actual experiment to avoid methodological biases. The ATCO's eyes' position was 2.1 m distance from the 56'' HD screens in order to standardize experimental conditions and to guarantee the necessary visual acuity. The experimenter sat at the participant's right side. The different FR modalities were ordered in a Latin square, in order to randomize the observations. After the last session, the participants answered a supplementary questionnaire in which they gave demographic information about themselves and classified the watched videos in order of preference. Finally, they were asked to give their general opinion on Remote Tower in order to reduce potential motivational biases followed by a general debriefing session.

IV. RESULTS

A. Results concerning visual performance

1) Adequate assessment of moving objects

In order to evaluate AAMO, the ATCOs' answers were coded as "1" when the movement is perceived "safe and efficient" and vice versa as "0" when the movement was perceived as "neither safe, nor efficient". It was observed that the movement of five objects was perceived as being "safe and efficient" by all ATCOs in each of the four FR modalities. These objects correspond to the propeller of three different aircraft on the apron, to a flag from which the ATCOs had to assess the wind direction and the direction of a flock of birds. Concerning the flock of birds, the ATCOs added that it was easy to identify the objects as birds and to deduce their direction.

The other category of objects corresponds to the flashing lights of three vehicles: a fuel truck, a black airport vehicle, and a follow me car. Concerning the fuel truck and the black vehicle, we observed that most ATCOs judged the visibility of the flashing light as being perceivable safe and efficient in the 5 fps, 10 fps and 15 fps conditions but not in the 2-fps condition. This tendency appeared especially regarding to the

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follow-me vehicle's flashing lights. In the 2-fps condition, a safe and efficient perception is only admitted one time out of 21 instances over all ATCOs. By comparing all means of all flashing lights instances (35 in total per FR over all 7 ATCOs), we observe that the flashing lights are perceived as being least visible in a safe and efficient manner in the 2-fps condition (M = 0.17, N = 7, SD = 0.21), followed by the 10-fps condition (M = 0.77, N = 7, SD = 0.34) and the 5-fps condition (M = 0.8, N = 7, SD = 0.31). In the 15-fps condition, flashing lights were perceived as the being most visible in a safe and efficient manner (M = 0.85, N = 7, SD = 0.25). A chi-square test supports this tendency: The perception of flashing lights decreases significantly when the FR drops from 15 fps to 10 fps, 5 fps and 2 fps ($\chi^2_{(df = 3, N = 7)}$ = 1, p < .01). But these results can only be found for flashing lights.

Thus $H_{1,1}$ is only partially assumed, i.e., by reducing the FR from 15 fps to 10 fps, 5 fps or 2 fps, the adequate assessment of flashing lights decreases but others remain unaffected.

2) *Visual Detection Tasks*

The mean detection times, centered on the mean to each of the four FR conditions, show that ATCOs take on average less time detecting an aircraft in the approach area at 10 fps (M = -1.4, N = 7, SD = 6.33) than at 15 fps (M = -0.04, N = 7, SD = 5.85), at 2 fps (M = 0.21, N = 7, SD = 5.36) or at 5 fps (M = 1.5, N = 7, SD = 4.32). However, a Friedman test did not show significant difference between ATCOs' reaction time at the four FR conditions ($\chi^2_{(df = 3, N = 7)}$ = 2.14, p = .54). Thus, the reduction of FR does not appear to decrease the ATCOs' performance to detect an aircraft in the final approach area which supports our $H_{0,2}$ to retain the H_0.

Furthermore, all aircraft in different traffic pattern positions, as well as all human beings on the movement and maneuvering area were perceived by ATCOs in each FR condition. In addition, some ATCOs add that the jerky movements perceived in the 2-fps and 5-fps condition helped them to detect the aircraft quicker. According to them, the jerky movements cause a blinking effect and thus attract more attention than an aircraft that moves more smoothly at 10 fps or 15 fps.

3) *Visual Tracking Tasks*

The measured times of VTT, again centered on the mean of each of the four FR conditions, indicate that on average, ATCOs could visually track departing aircraft longer at 15 fps (M = 1.48, N = 7, SD = 3.95) than at 2 fps (M = -0.05, N = 7, SD = 4.98) or at 5 fps (M = -0.35, N = 7, SD = 8.44), worst at 10 fps (M = -1.06, N = 7, SD = 4.75). Again, the Friedman test could not reveal significant difference of ATCOs' performance to visually track aircraft in all tested four different FRs ($\chi^2_{(df = 3, N = 7)}$, p = .62), which supports our $H_{0,3}$ to retain the H_0.

B. *Results concerning physiological stress*

After each test run, participants answered the 16 SSQ items on a Likert scale ranging from "0 = none", "1 = slight", "2 = moderate" to "3 = severe".

At the beginning, we checked whether the results of the experimental ATCO group differ significantly from the pseudo-ATCO control group to exclude systematically effecting variance in terms of possible motivational biases on behalf of the ATCOs caused by their general attitude towards the Remote Tower concept. A t-test for independent samples for the Total Sickness Score (TSS) shows that there is no significant difference found between both groups ($t_{(10)}$ = 0.59, p = .56). Thus, only results of the expert group are taken into account for all analyses. Fig. 2 depicts that with a mean TSS of 1176 we observed only under averaged TSS means for all four test conditions: 15 fps (M = 24.3, N = 7, SD = 19.56), 10 fps (M = 37.5, N = 7, SD = 44.66), 5 fps (M = 50.03, N = 7, SD = 71.94), 2 fps (M = 147.06, N = 7, SD = 213) (for the exact calculation of the TSS refer to [27]).

Still marginal, but the highest TSS is measured at 2 fps (see Fig. 2). A Friedman test could not reveal significant difference between "base" and the four test conditions neither for the TSS ($\chi^2_{(df = 4, N = 7)}$ = 5.89, p = .21), nor for the subscale "Nausea" ($\chi^2_{(df = 4, N = 7)}$ = 8.88, p = .06), the subscale "Oculomotor" ($\chi^2_{(df = 4, N = 7)}$ = 3.93, p = .42), or for the subscale "Disorientation" ($\chi^2_{(df = 4, N = 7)}$ = 5.29, p = .26). As postulated, $H_{0,4}$ is to be retained: The psychological stress of operators did not decrease significantly when FR is reduced from 15 fps to 10 fps, 5 fps or 2 fps.

C. *Results concerning the perceived video quality*

Via a 7-point Likert scale ranging from "1 = totally unacceptable", "2 = unacceptable", "3 = slightly unacceptable", "4 = neutral", "5 = slightly acceptable", "6 = acceptable" to "7 = perfectly acceptable", ATCOs perceived

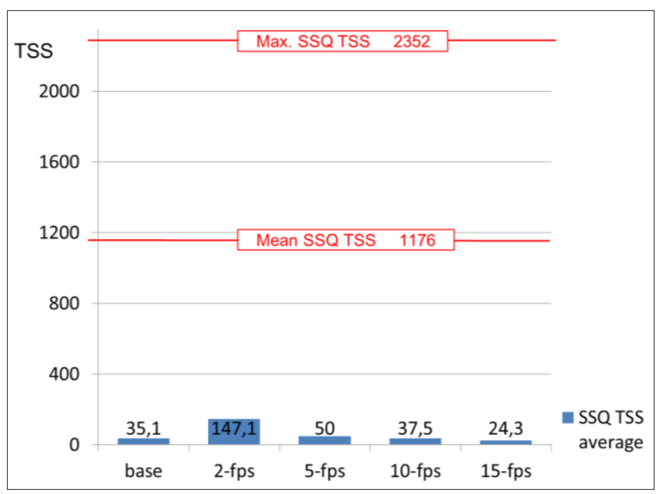

Figure 2. Total Sickness Scores before (base) and for four different FR test conditions.

the video quality as being more acceptable at 15 fps (M = 5.71, N = 7, SD = 1.25, Min = 3, Max = 7) than at 10 fps (M = 4.86, N = 7, SD = 2.67, Min = 1, Max = 7), 5 fps (M = 4.29 , N = 7 , SD = 1.8 , Min = 1 , Max = 6) or at 2 fps (M = 3, N = 7, SD = 1.53, Min = 1, Max = 5).

The more the FR is reduced, the more ATCOs judge the quality of the video as being less acceptable. In the 2-fps condition, the quality was even rated below the average “neutral”. This tendency is supported by a Friedman test that revealed significant difference ($\chi^2_{(df = 3, N = 7)} = 12.05$, $p < .01$). As postulated in $H_{1,5}$, the perceived video quality in terms of FR decreased with the reduction of the FR.

After each test run, the ATCOs were asked to estimate the FR of the just watched video. Surprisingly, ATCOs always believed that the FR is superior to what it actually was: Answers after the 2 fps conditions referred to 3.14 fps by average, 5 fps to 6.29 fps, 10 fps to 15.29 fps, and 15 fps to 20.14 fps. By average they overjudged the FR by 53.9%.

After having completed all test runs, the ATCOs were asked to rank the watched videos in their order of preference. Most of them ranked 15 fps at the top. The second rank is mostly shared by videos at 5 fps or 10 fps. The last rank is notably reserved for the 2 fps.

D. Results concerning the perceived operability of a low FR system

On a 7-point Likert scale from “1 = totally disagree”, “2 = disagree”, “3 = somewhat disagree”, “4 = neither agree nor disagree”, “5 = somewhat agree”, “6 = agree” to “7 = strongly agree”, the ATCOs should answer the following statement: “I would be able to control the air traffic with the given FR.”. The perceived operability increased with the increase of FR. Thus, the system operability was perceived least at 2 fps ($M = 2.86$, $N = 7$, $SD = 1.57$, $Min = 1$, $Max = 5$). It increases over-averaged with 5 fps ($M = 4.14$, N = 7, $SD = 1.87$, $Min = 1$, $Max = 6$), 10 fps ($M = 4.86$, $N = 7$, $SD = 1.57$, $Min = 1$, $Max = 7$) and finally with 15 fps ($M = 5.71$, $N = 7$, $SD = 1.25$, $Min = 3$, $Max = 7$). A Friedman test revealed this difference as significant ($\chi^2_{(df = 3, N = 7)} = 12.68$, $p < .01$). Even though only the 2-fps condition is judged below acceptable, $H_{1,6}$ is to be assumed: The lower the FR, the less ATCOs consider the system as being operable.

V. Discussion

The effects of lower FRs on the performance of an adequate assessment of moving object tasks are multilayered and cannot be judged generically. Surprisingly, all propeller movements, the wind flag and the flock of birds, as well as the movement of human beings on the aerodrome were perceived by all ATCOs in all four FR conditions in a safe and efficient manner. Most ATCOs commented that the rapid disappearance of the bird flock over the runway made them worry much more than their jerky movement, which refers rather to an image resolution problem than to a lower FR. Concerning the flashing lights, most ATCOs judge flashing lights to be perceivable safely and efficiently down to 5 fps but when further reduced down to 2 fps the capturing of the rotating beacon at its full brightness decreased and the perception was no longer perceived as being safe and efficient by the majority of ATCOs. Those negative effects in 2 fps was expected and could be covered by using flashing lights with obscure/luminous phases that interfere less with the chosen FR.

As postulated, with respect to the performance in visual detection tasks inferential statistics do not indicate a significant difference between the four FR conditions. Apart from the impression that aircraft seem to move jerkier at lower FRs, especially when they are close to the camera, FR does not seem to play an essential role in detection tasks. In particular planes in the final approach or departure area do not have great lateral movements at all. ATCOs therefore perceive only a point that grows bigger when the plane approaches or shrinks at departure. The concern of not visually detecting an approaching or departing aircraft or an aircraft right downwind due to lower FRs seems therefore be unjustified. In addition, it seems more logical to detect an approaching aircraft earlier or to see an aircraft leaving the aerodrome longer by increasing the image resolution instead of higher FRs. Moreover, even if the movement seemed jerky at times, several ATCOs noticed that the “jumpy” aircraft even attracted their attention.

Physiological stress was tested via the SSQ after each run. As presumed, the inferential results show that no negative effects with respect to physiological stress could be measured. All TSS were under averaged low. Only in the 2 fps condition the severity of the symptoms increased slightly for some ATCOs, but far from any significance. Someone could argue that these findings are biased by very positive beliefs or attitudes towards lower FR system. This potential side effect could be mitigated by using a pseudo-ATCO control group who performed the entire experiment but by definition had a neutral attitude towards lower FRs since they were not involved in the Remote Tower business: Both groups did not significantly distinguish in their SSQ scores. Thus, a systematical effect of bias for the experimental group could be excluded. For the correct interpretation of these results, it is also important to note that the study was dealing with a small sample one can refer to as a sample of experts [11]. In other words, they share some personality characteristics and very specific professional skills, as well as specialized selection and education criteria. Thus, it is very likely to transfer the results found in the inferential statistics to other ATCOs. For an implementation of a Remote Tower with a medium image resolution and low FRs from 2 fps to 15 fps, it can be stated that effects expressed by physiological stress will most likely not appear.

As expected, the perceived video quality decreased significantly with the reduction of FR. These results are not that surprising since air traffic control requires high visual performance and reducing the FR is an obvious loss in terms of video quality. But in the real Remote Tower implementation world, this obvious loss of video quality could be compensated by an increase of image resolution. Since lower FRs seem not to impair detection performance nor induce physiological stress, this trade-off between FR and image resolution seems to be a valid approach to keep bandwidth consumptions low but better adapt the visual presentation to the air traffic service operators' task: For detecting small aircraft in a far-view distance, high image resolution is needed and FR is not this important. To assess the velocity of aircraft in a near-view distance on the taxiways or apron, higher FRs are essential and image resolution would not play such a significant role. As stated before, this compensation approach could not be realized in the experimental setting, but it can be assumed that the ATCOs' perceived video quality would have been more balanced over the different FR conditions if have done so.

Similar to the results of perceived video quality are the ones concerning the perceived system operability. By no surprise, also a significant difference between the four FR conditions was found. The average of ATCOs "disagree" or "somewhat disagree" about thinking to be able to handle air traffic at 2 fps. At 5 fps and 10 fps, ATCOs expressed to "slightly agree" being able to manage air traffic and at 15 fps, they expressed to "agree". Like already stated above, the experimental setting neglected compensation in terms of image resolution which would probably have balanced the ATCOs' attitude as well.

To conclude the discussion on our findings, we can affirm that according to our results, a system at lower FR is justifiable at least starting from 5 fps. Thus, between 5 fps and 15 fps, the air controllers' visual performance is maintained at the same level. If one wants to set up a lower FR system, one should pay particularly attention to the used flashing lights at the aerodrome in order to choose some which do not interfere with the FR.

Concerning physiological stress, we did not find a significant increase of the scores when the FR is reduced from 15 fps to 2 fps. However, the comparison of the means in the descriptive statistics suggests a slight increase in the TSS at 2 fps. To avoid physiological stress at a system similar to the one at BWE, we recommend rather 5 fps, 10 fps or 15 fps.

With respect to the perceived video quality, the ATCOs preferred higher FRs to lower FRs. They were mostly opponent against 2 fps. In summary, if one wants to operate Remote Tower at a low FR, it is important to develop convincing strategies to increase the tolerance towards low FR. From a psychological point of view, it is not advisable to put ATCOs in front of a 2-fps system hoping that they will accept it. The user centered approach teaches us how important it is for users to experience positive emotions in order to raise acceptability for a new product [34]. Once the video quality of the low FR system is accepted by the ATCOs, the fear of getting sick could be taken away from them and self-efficiency for performance could rather be perceived. By consequent, it is likely that the attitude towards the perceived system operability is expressed more positively.

Further operational simulation and field trials with the operator in the loop are recommended to increase confidence in low FR systems and to gain additional feedback from ATCOs to develop bests designed Remote Tower solutions for the given operational environment.

VI. Conclusion

The optimal FR in Remote Tower environments is debated amongst many actors of the Remote Tower community: It must not be too low to endanger safety or operators' health, but also not be too high to increase the consumption of bandwidth or to compromise other parameters like image resolution. The results of this study can mitigate the concerns regarding lower FR settings. The major conclusion of this study is that the visual performance and physiological stress were not affected by lower FRs in between of 15 down to 2fps. In particular, these findings will allow more degrees of freedom in the design process of a Remote Tower implementation to best adapt a local solution to their operational environment. In future research, it remains to be studied how a trade-off between lower FRs and compensation by higher image resolution would be judged by the ATCOs.

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