ROTORCRAFT SAFETY: A SIMULATOR-BASED TRAINING PERSPECTIVE

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Abstract
Training has the potential to inject a "*safety vaccination*" into the rotorcraft community by reducing the number of accidents. The term training should not be intended only in a strict sense, i.e., as pilot technical skills training, but more broadly as risk avoidance and safety culture training. As in the case of vaccination, where immunity is created only when applied on a large scale, helicopter accidents will not be eradicated until every player in the rotorcraft community is involved in the safety enhancement process. In particular, as outlined by accident and safety reports, a reduction in the helicopter accident rate cannot be accomplished disregarding pilots' training and the contribution that flight simulators can provide to both training and certification. This paper provides an overview of the research into simulator training for helicopter pilots conducted as part of the European Joint Doctorate NITROS (Network for Innovative Training on Rotorcraft Safety). An approach that requires an in-depth analysis of the actual training task is adopted for two different maneuvers, namely hover and autorotation. This approach enables the training developer to understand what are the aspects of the actual training situation that should be reproduced in the simulated training situation to avoid ineffective training and negative transfer of skills. Moreover, such an approach allows to identify differences in terms of requirements between the training of basic and advanced maneuvers and between initial and recurrent training. The results of three different pilot-in-the-loop experiments, performed to explicitly confirm the effectiveness of developed training programs and to understand whether certain elements of the simulation can foster the development of superior flying skills, are summarized in this paper.

1. INTRODUCTION

Although the first studies on helicopters date back to Leonardo da Vinci's "airscrew" in 1493, well in advance of the first fixed-wing airplanes, the first successful helicopter design, the VS-300, upon which conventional helicopters are currently based, was conceived by Sikorsky in 1939, more than 30 years later than the Wright Flyer [1].

The outward clumsiness and lack of clean and elegant lines of a helicopter, which may result in the appearance of a "flying brick" to the layman's eye, is compensated by a remarkable versatility, which is the source of its widespread application. Indeed, helicopters have become an essential means of transport and have provided invaluable help in both civil and military contexts, such as air ambulances and search and rescue.

The 30 years delay with respect to fixed-wing aircraft development, the problems posed by helicopters in terms of aerodynamics, engineering, stability and vibrational control and the hostile operational environment in which they are usually involved are the root causes of the higher accident rate for rotary-wing aircraft compared to airplanes. This negative historical trend led also to a negative public perception of helicopter flight safety.

To revert this trend, many rotorcraft safety initiatives were launched since 2005, starting from the International Helicopter Safety Team (IHST), which was based on the Commercial Aviation Safety Team (CAST) model[2]. The CAST revealed itself to be very successful in reducing the number of accidents occurring in commercial aviation. However, that was a relatively easy task, because all of the operators involved in commercial aviation are well organized companies with safety management systems already in place. A different situation is being faced by the IHST, which is dealing with every type of helicopter operations. Therefore, there is a need to communicate not only with commercial operators (e.g., passengers carrier, offshore, aerial work, etc.), but also with non-commercial operators, such as pilot training schools and private pilots.

It is clear that a safety enhancement is possible only through a partnership between the authorities and the rotorcraft community and industry. Thus, not only the rule-makers and the manufacturers, but also the operators, the private pilots, the research institutes, and the universities should be kept in the loop.

Although still far away from the zero (fatal) accidents target, as called for by Harris[3] in 2007, all the rotorcraft safety initiatives are helping to develop a proactive approach to enable an early solution to accident causes that are not clear yet. Therefore, the European Joint Doctorate NITROS (Network for Innovative Training on Rotorcraft Safety) project (Fig. 1) focused directly on improving rotorcraft safety by training Early Stage Researchers (ESR) to develop a mindset based on design for safety and use it to tackle critical aspects of rotorcraft design. As part of the NITROS project, the research presented in this paper has been performed by ESR 12 and concerns simulator training for helicopter pilots, which was identified by safety reports as one of the most crucial interventions to reduce helicopter accident rates[4–7].

The value of flight simulation in pilot training is unquestionable. The development of flight training devices enables trainees to conduct a significant part of flying training on the ground, with consequent benefits in terms of safety and costs.

The advent of analogue computing and the subsequent onset of digital computers led to a significant improvement in the fidelity of flight models that can be run in real-time[8]. Advances in motion and visual systems were also possible thanks to the growth in computational power and the decrease of electronic components size[8].

The simulation industry has always been driven by improved realism. Indeed, the use of sophisticated and advanced technologies makes a flight simulator more attractive to be procured[9]. However, this approach is leading to flight simulators that are almost as complex and expensive as the aircraft they should replace. Furthermore, flight simulators that are mainly based on a technology-push process sometimes are not fit for the specific training purpose[9].

Therefore, the needs of the specific training task should always cover a prominent role with respect to simulator complexity during the development of a training program[10]. The training developer must understand what characteristics of the task must be emphasized in order to train someone to perform that task[9,11]. This is often achieved through interviews to subject matter experts (persons familiar with the type of tasks to be trained) to determine how the training system and associated training media should be configured to meet the requirements[11].

The specification of training media characteristics is often referred to as the "*fidelity question*"[11]. Essentially, the fidelity question asks how similar to the actual task situation a training situation must be to provide efficient and effective training. A conceptual bridge is necessary to link the actual task requirements to the characteristics of the training system, which will never replicate the actual aircraft exactly. Not to mention the inevitable differences in psychological factors that come with training in an intrinsically safe environment for situations that could be lethal in the real operation.

This paper provides an overview of NITROS ESR 12's research, which was conducted to investigate procedures to prevent or alleviate the occurrence of flight simulator negative transfer of training. Two different training tasks, hover and autorotation, were considered to address the needs deriving from both initial and recurrent pilot training. The research was initially devoted to analyze the hover maneuver and a first study[12] was performed to assess the effectiveness of a part-task training for initial hover training in flight simulators, and to better understand to what extent the low-level hover skills developed by task-naïve learners on a low-fidelity simulator are effectively transferred to a more realistic simulation environment.

The attention was then shifted towards the analysis of the autotoration maneuver[13] and two experiments[14,15] were conducted to determine whether certain dynamics may lead to the development of a more robust control behavior that can be easily adapted to different system dynamics, thus leading to substantial benefits during autorotation training.

An overview of the results of these studies will be provided in the next sections according to the following structure. First, an in-depth analysis of the needs of each training task is performed and a training program is developed accordingly (Sec. 2.1 and 2.2). Then, pilot-in-the-loop experiments are con-

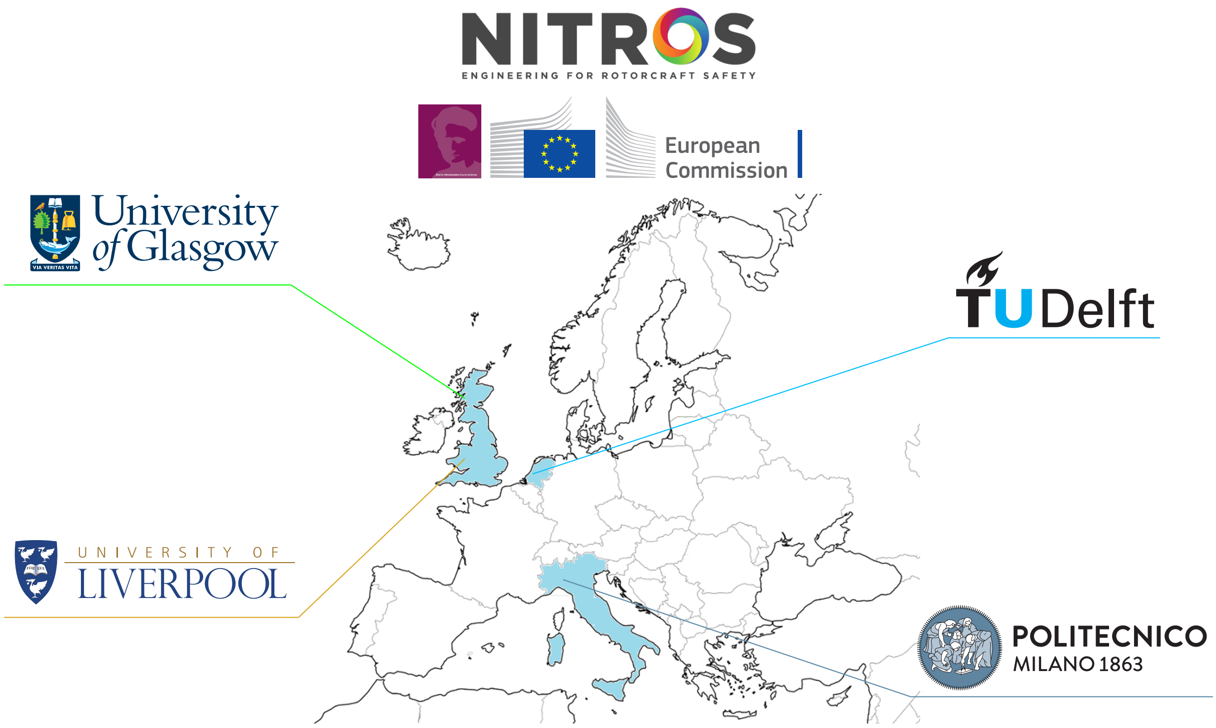


Figure 1: NITROS (Network for Innovative Training on Rotorcraft Safety) universities network.

ducted to evaluate the effectiveness of the training designed for each task (Sec. 3). Finally, limitations of current flight simulators are analyzed in the light of the results obtained in the experiments and advice is given on techniques to avoid unrealistic training or, at least minimize, the chance of negative transfer (Sec. 4).

2. ANALYSIS OF THE TRAINING TASKS

Hundreds of accidents investigation reports have been analyzed by the helicopter safety teams[4–7] with the purpose of identifying safety issues and suggestions for safety enhancement. To achieve this goal, they adapted the process used successfully by the Commercial Aviation Safety Team (CAST) to make it consistent with characteristics and potential limitations present in helicopter data[2].

The analyses carried out by the U.S. Joint Helicopter Safety Analysis Team (JHSAT)[4,5] and the European Helicopter Safety Analysis Team (EHSAT)[6,7] both highlight the same issues of concern and the same improvement actions. Most of the accidents in the data set were the result of pilot-related factors, such as pilot judgement and actions, ground duties and pilot situational awareness (Fig. 2). For this reason, recommendations to prevent accidents are predominantly related to the Training/Instruction and Safety Management interventions (Fig. 3).

An examination of Intervention Recommendations at the Level 3 details more specific recommendations for a specific Level 1 group. This is done in Fig. 4 for the Training/Instructional category, which shows the top 10 Level 3 Intervention Recommendations for this category according to the analysis conducted by the U.S. JHSAT[4,5]. It is worth mentioning that the top 10 Level 3 Training/Instructional Intervention Recommendations are also enumerated among the top 20 overall Intervention Recommendations. Fig. 4 enables us to understand what are the training aspects that still need to be consolidated. The development of a standardized training program for autorotation and emergency aircraft handling, as well as the improvement of simulator training for basic and advanced maneuvers, are therefore essential to enhancing helicopter safety.

For this reason, two different tasks have been analyzed in this research: hover and autorotation. In this way, it is possible to gain insight into the differences in terms of training requirements for basic and advanced maneuvers and for initial and recurrent training.

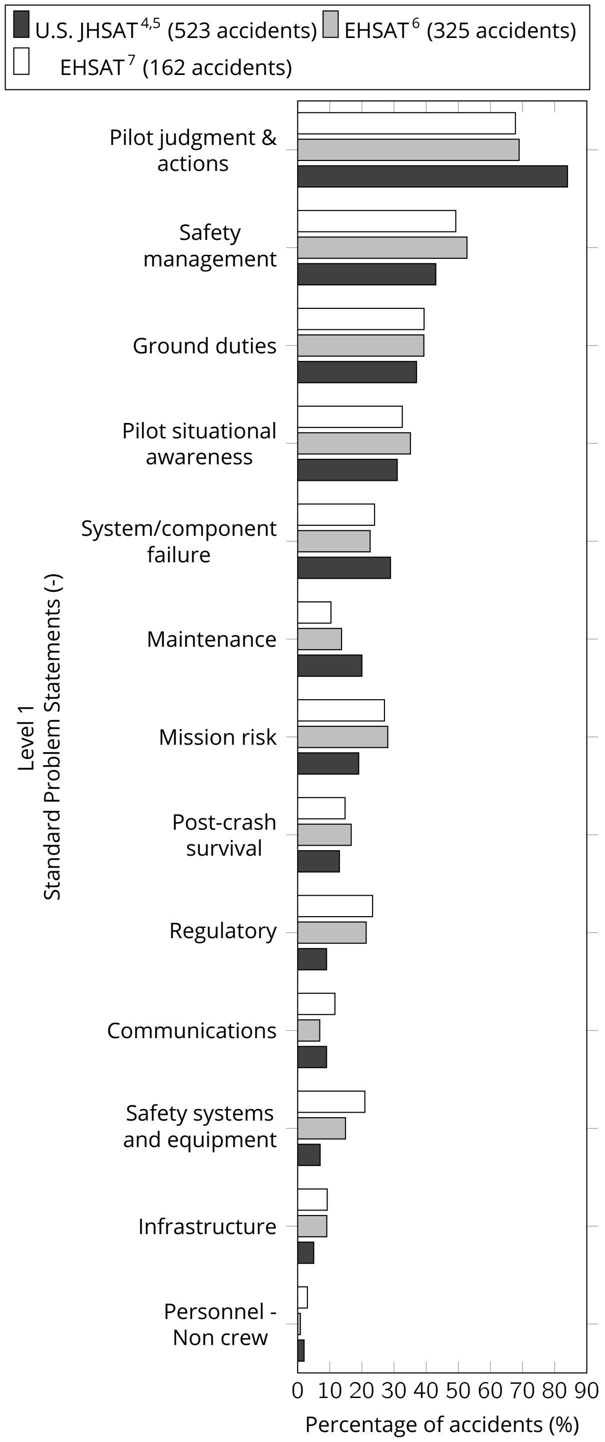


Figure 2: Percentage of analyzed accidents where Level 1 Standard Problem Statements was assigned at least once[4–7].

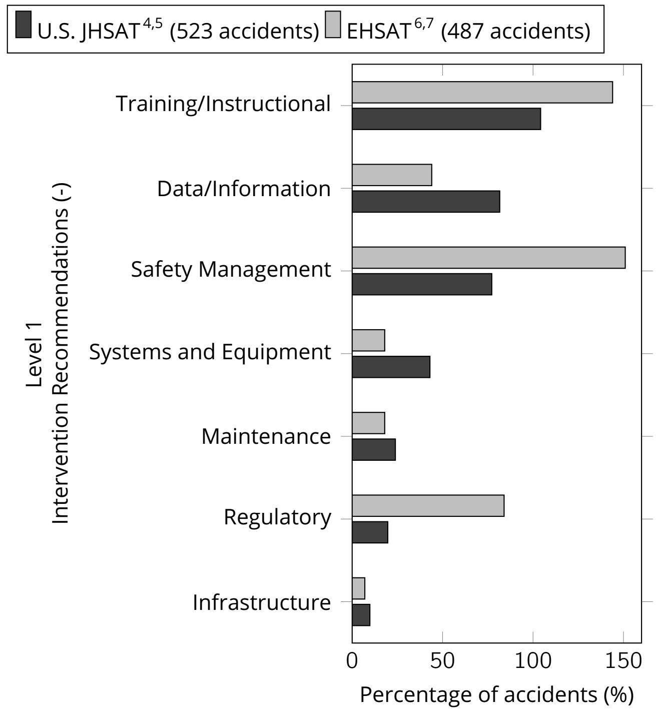


Figure 3: Percentage of analyzed accidents where Level 1 Intervention Recommendations was assigned at least once[4–7].

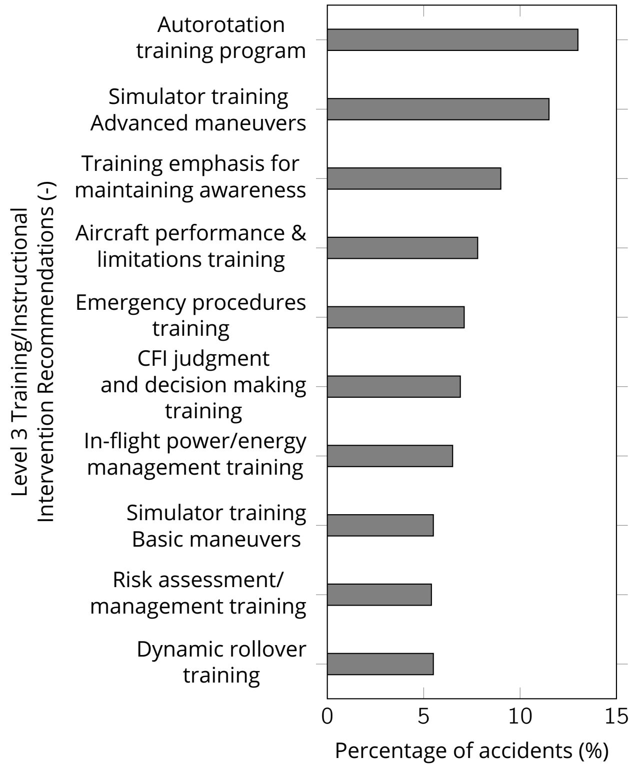


Figure 4: Top 10 Level 3 Training/Instructional Intervention Recommendations[4,5] (523 accidents).

2.1. Basic Maneuver: Hover

The ability to hover is the main capability that differentiates helicopters from fixed-wing aircraft. It is a basic flight maneuver and, as such, it is essential for helicopter pilots to master it. Therefore, hover is the first maneuver that student pilots learn to perform. Instructor pilots usually teach this task by dividing it in sub-tasks and taking advantage of the dual flight controls. The foundations of this "*part-task*" teaching method lie in cognitive psychology. In particular, Sweller developed an instructional design theory, called Cognitive Load Theory (CLT), that reflects the way humans process information[16,17].

Cognitive Load Theory provides a basis for predicting that training strategies reducing the intrinsic load of a task during training enable more resources to be devoted to learning[18]. Two closely related strategies that accomplish this goal, either by simplifying tasks in early training trials or by dividing tasks in parts, are increasing difficulty (ID) and part-task training (PTT), respectively.

Task-naïve learners benefit more from load-reducing strategies during the training process than experienced learners do. For this reason, a part-task training for initial hover training in flight simulators was developed at the Max Planck Institute for Biological Cybernetics[19], after consultation with an instructor pilot. This part-task training proved to be effective in a number of quasi- and true-transfer-of-training experiments[20,21] and consists of a sequence of five tasks characterized by an increasing level of difficulty and intended to teach the role of each flight control with a step-by-step approach. To achieve this goal, an autopilot based on optimal control theory was designed[22,23]. This autopilot mimics the behavior of an instructor pilot sitting next to his student and acting on the dual controls to help him. Specifically, the five tasks were defined as follows:

1. *Left/Right Hovering Turn* (Fig. 5a). In this task, the student pilot controls only the pedals. All the other axes are controlled by the autopilot. This maneuver starts in a stabilized hover at an altitude of 25 ft (≈ 7.5 m) in front of a hover board, placed 360 ft (≈ 110 m) in front of the starting position. The target is oriented $90°$ to the left and identified by an equally distant hover board. After reaching the target, the heading is to be maintained for 10 seconds. This maneuver is then to be repeated referring to a target oriented $90°$ to the right.

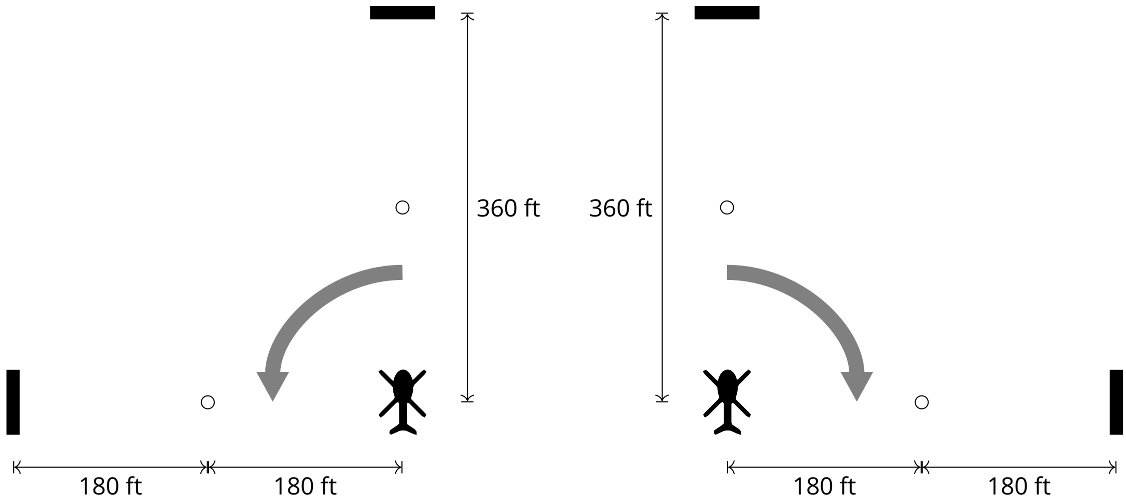
2. *Up/Down Vertical Repositioning* (Fig. 5b). In this task, the student pilot controls only the collective. All the other axes are controlled by the autopilot. This maneuver starts in a stabilized hover at an altitude of 25 ft (≈ 7.5 m) in front of a hover board, placed 300 ft (≈ 90 m) in front of the starting position. Additionally, a blue sphere is placed half way between the starting position and the hover board to aid the student pilot in maintaining the correct vertical position. The target is placed 50 ft (≈ 15.25 m) above the starting position and identified by equally distant hover board. After reaching the target, the altitude is to be maintained for 10 seconds. This maneuver is then to be repeated in the opposite direction, starting in a stabilized hover at an altitude of 75 ft (≈ 22.75 m).

3. *Up/Down Vertical Repositioning and Heading Hold* (Fig. 5b). This maneuver is analogous to the previous one. However, in this case the student pilots need to control also the pedals and to compensate the couplings related to the use of the collective lever. All the other axes are controlled by the autopilot.

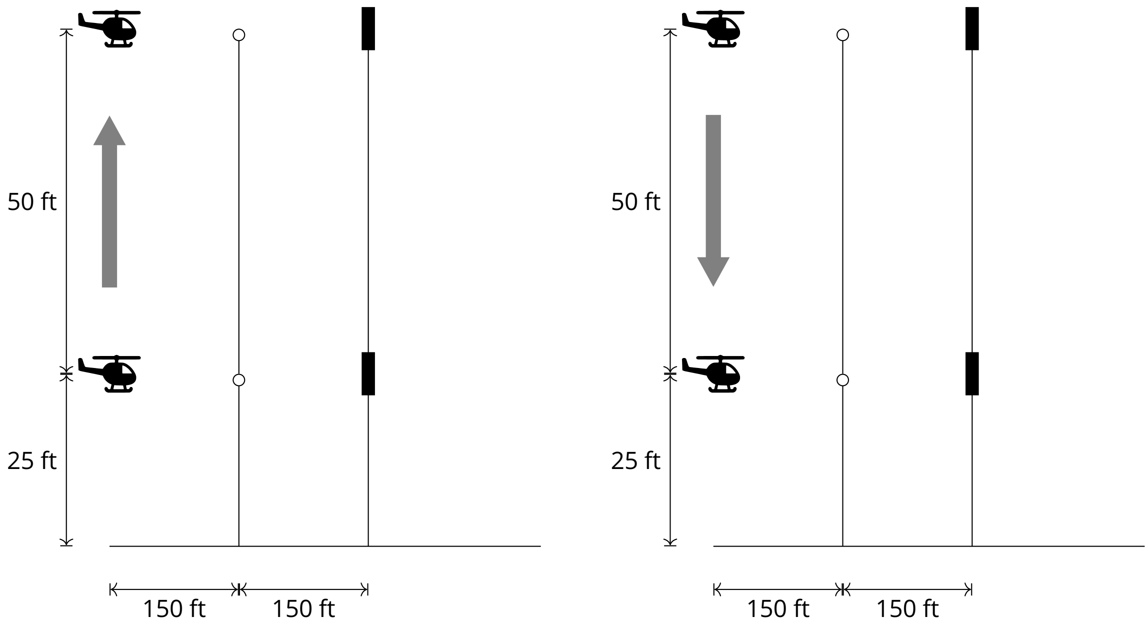
4. *Cyclic Control Hover* (Fig. 5c). This maneuver starts in a stabilized hover at an altitude of 25 ft (≈ 7.5 m) in front of a hover board, placed 360 ft (≈ 110 m) in front of the starting position. The student pilots control only the cyclic stick and their objective is to maintain the helicopter in hover for 30 s minimizing position and heading error. All the other axes are controlled by the autopilot.

5. *Full Control Hover* (Fig. 5c). This maneuver is analogous to the previous one. However, in this case the student pilots need to control also the pedals and the collective. Therefore, the autopilot is disengaged.

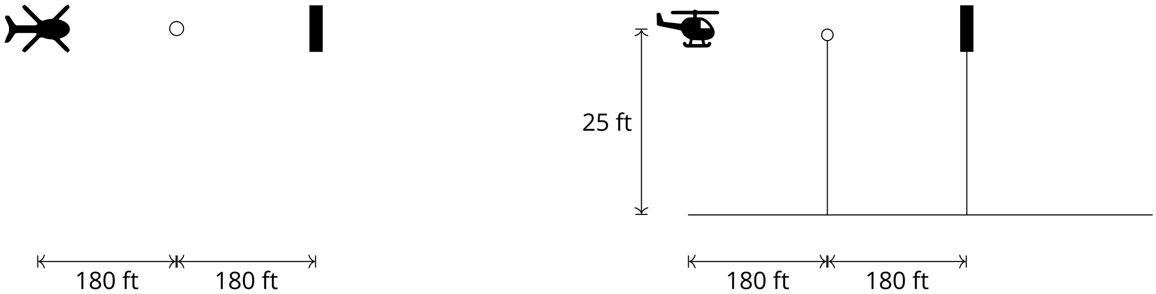
This training program was used in a quasi-transfer-of-training experiment[12], that was conducted as part of NITROS ESR 12 research and that is described in detail in Section 3.1.



(a) Left/right hovering turn.



(b) Up/Down vertical repositioning (with and without automatic heading hold).



(c) Cyclic control and full control hover (top view on the left and side view on the right).

Figure 5: Hover part-task training program[12,19–21].

2.2. Advanced Maneuver: Autorotation

Another critical training scenario is represented by autorotation, which is a technique used by helicopter pilots to reach the closest suitable landing site in the event of partial or total power failure.

Whether due to an actual emergency or during the training for such an event, autorotations often result in an accident in which the pilot fails to perform the maneuver correctly[4–7]. To minimize risks during practice autorotations and to make training as effective as possible, it is necessary to develop a standardized training program for autorotation. Furthermore, to reduce the burden on the instructor, the student should learn the basics of maintaining/controlling the airspeed and the rotor RPM before practicing autorotation. This can be achieved through a number of exercises that are preparatory for autorotation[24]:

- *Engine deceleration checks*: to avoid that a practice engine failure becomes a real one, it is essential to check that the throttle and fuel control are going to respond correctly when the engine is put to idle.
- *Rotor RPM decay rates*: the instructor will show how different power/collective settings affect the rate of decay of rotor RPM once the engine is disengaged.
- *Attitude on the ground and in hover*: the instructor will show these two different pitch attitudes by pointing out where the horizon crosses the windshield central pillar with respect to a convenient rivet or any other reference point on the deck, as these two cues will be used at the end of the flare.
- *Counting down to touchdown*: the student will learn to sense the position of the skids with respect to the ground.
- *Hover engine failures*: the student will learn to:
  - First stop the lateral drift due to the reduction of the tail rotor effectiveness to avoid tip over when touching the ground.
  - Stop the yaw. There is no need to return to the original heading.
  - Cushion the touchdown: try at first from a very low height to help the student judge collective lever application.
- *Running landings with power at slow forward speed*: the instructor will teach the student not to lower the collective until the forward motion has stopped.
- *Hover taxi engine failures*: this task is similar to hover engine failures.
- *Quick stops*: they duplicate most of the flare part of the autorotation quite well and they are an excellent coordination exercise for beginners.
- *Steady descent in autorotation*: the instructor will teach the student the basics of maintaining/controlling the airspeed and the rotor RPM by simulating an engine failure at a higher-than-normal altitude.
- *Entry to autorotation*: the student will learn the symptoms of an engine failure and the correct reactions to be able to respond instinctively.
- *Flare*: the student will learn to stop the rate of descent and reduce the airspeed.
- *Power recovery or Touchdown*: A power recovery autorotation terminates in a hover as opposed to landing without power. This is always possible in a training situation, because the engine failure is not real, but simulated by disengaging the rotor shaft from the power shaft by means of a clutch with the engine in an idle state.

Autorotations to touchdown are seldom practiced during civil in-flight training, due to the high risks involved in the touchdown part of the maneuver. In the best case scenario, poorly executed autorotations during in-flight training may damage the helicopter. For this and other reasons, such as avoiding wearing out the skids, many flight schools prefer to teach only autorotations with a power recovery.

However, to avoid unrealistic practice from the flare to the touchdown, the maneuver should not terminate with a power recovery[25]. This is true especially for helicopters with free turbine engines, i.e., engines in which the power turbine is not mechanically linked to the compressor turbine. For this type of engine, the power turbine extracts power from the the exhaust stream of the compressor turbine. This means that even in ground idle setting, the engine is still burning fuel to keep the compressor turning and its hot exhaust gases are impinging on the power turbine, resulting in a residual turbine output power. If the turbine and rotor tachometer needles are split, then because of the free-wheeling unit, no power is being transmitted to the rotor system. However, in the event of low rotor speed, the two needles are joined and some power will still be transmitted, resulting in an unrealistic practice, because the helicopter appears lighter than it really is and the rotor system appears to have less drag than it really has and more inertia during the final flare. When the pilot is exposed to a real power-out situation for the first time, the apparent loss in rotor performance can cause dramatic consequences.

This demonstrates the importance for the pilots to train with helicopters with different handling characteristics (e.g., different rates of descent, size, weight, rotor inertia, agile/sluggish dynamics) to be prepared for the unexpected, because the variety of conditions that pilots may face during emergencies requires experience and judgment in order to react promptly and avoid the many possible errors.

For this reason, helicopter dynamics was chosen as the independent variable in two quasi-transfer-of-training experiments [14,15], that were conducted as part of NITROS ESR 12's research (see Section 3.2).

3. PILOT-IN-THE-LOOP EXPERIMENTS

Transfer-of-Training (ToT) experiments are one of the few available techniques that can be used to explicitly measure simulator training effectiveness [26]. Quasi-transfer studies, also known as Simulator-to-Simulator Transfer experiments, employ tasks where participants alternate between different simulators or where some change in task or configuration is performed in the same simulated environment. In contrast, real-flight-transfer studies investigate whether certain skills can be acquired in a simulator and successfully transferred to actual flight.

Three quasi-transfer-of-training experiments have been conducted to examine the relevance of the "*theoretical*" analyses of the training tasks presented in Section 2. The results of these experiments are presented in the following sections.

3.1. Effectiveness of a Computer-Based Helicopter Trainer for Initial Hover Training

A quasi-transfer-of-training experiment was conducted at the Max Planck Institute for Biological Cybernetics to assess the effectiveness of the hover training program introduced in Section 2.1 and to better understand to what extent the low-level hover skills developed on a low-fidelity simulator are effectively transferred to a more realistic simulation environment [12].

Twenty-four subjects with no prior flight experience, neither in actual helicopters nor in simulators, were trained to perform the hover maneuver controlling an identified model of a Robinson R44 civil light helicopter [27,28]. They were divided over two groups. The first group (the "experimental" group) was trained in a desktop trainer, referred to as Computer Based Trainer (CBT) (Fig. 6a), and then transferred to a high-fidelity simulator, the CyberMotion Simulator (CMS) (Fig. 6b). The second group (the "control" group) received the entire training in the CMS (Fig. 6b).

The experiment was divided into three phases (Familiarization, Training and Evaluation) and was carried out on two different days, as shown in Tab. 1. In total, each participant was trained in the simulators for approximately 3 hours. The analysis of the results focused only on the Training and the Evaluation/Transfer phases and is based on several metrics, such as the number of completed trials in each phase and the average root mean squared (RMS) position error with respect to the target hover position, heading error and linear velocity error.

Fig. 7 shows the absolute and relative numbers of completed trials by participants of both groups in each phase. The individual data points for each box plot are shown next to it (filled circle markers), together with the mean value (diamond marker). It was found that the experimental group (CBT) had a higher success rate than the control group (CMS) during the training phase, with an average number of completed trials that is almost twice as high. This marked difference disappears in the evaluation phase, where performance of the CBT group remains almost unchanged. In the last session of the experiment, participants of both groups were able to stabilize the helicopter model in the CMS, on average, in 60% of the runs, suggesting the effectiveness of the training program.

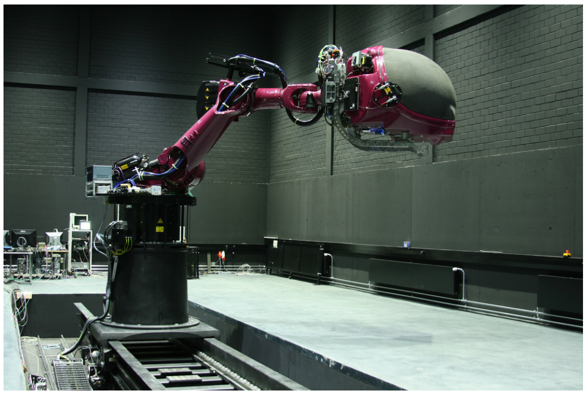
The dramatically smaller number of completed runs for the CMS group during the training phase was, in hindsight, related to the stricter safety limits in the CMS. Furthermore, some of the participants in the CMS group may have been overwhelmed by the CMS, which is characterized by a high vibration level and by a small cabin equipped with a large FOV projection screen.

According to the conducted statistical tests, the CBT group significantly improved its performance from the training phase to the evaluation phase for every considered performance metric, except for the vertical position score and the heading score.

No significant differences were found between the two phases for the CMS group. The participants of this group were not able to stabilize the helicopter in a large number of trials during the training phase. During the evaluation phase, they reached a level of performance close to that shown by the participants who were able to complete the task throughout the training phase.

At the end of the experiment, the two groups achieved equivalent performance. Indeed, the data

(a) The Max Planck Institute Computer Based Trainer (CBT).



(b) The Max Planck Institute CyberMotion Simulator (CMS)[29].

Figure 6: Flight simulators used in the experiment: the Computer Based Trainer (a), and the CyberMotion Simulator (b).

Table 1: Hover experiment phases[12].

Phase	Experimental group	Control group	Duration
Familiarization (Day 1)	Instructions session	Instructions session	15 minutes
	Part-task training in the CBT	Part-task training in the CMS	1 hour and 45 minutes
Training (Day 1)	Hover with all controls in the CBT	Hover with all controls in the CMS	30 trials of 30 seconds each
Evaluation/Transfer (Day 2)	Hover with all controls in the CMS	Hover with all controls in the CMS	30 trials of 30 seconds each

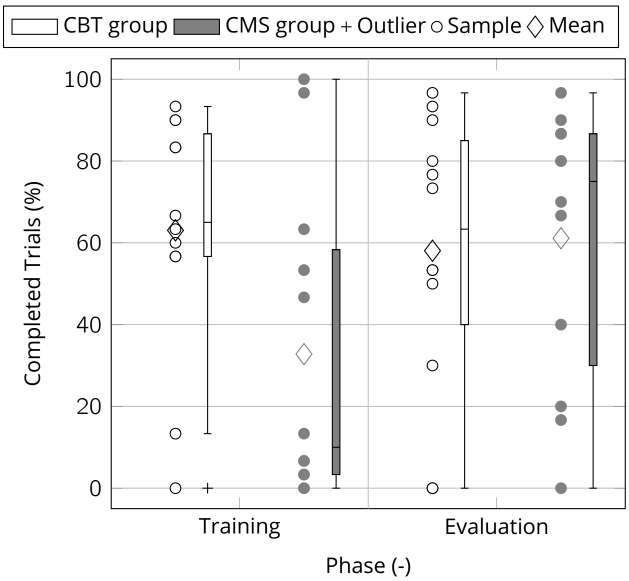


Figure 7: Distribution of the percent number of completed trials by participants of both groups in each phase[12].

of the two groups were not statistically different in any phase of the experiment. Overall, this findings suggest that desktop trainers may be a valid alternative to high-fidelity simulators not only for instrument and navigation training, but also for the training of low-level flying skills, if supported by a suitable training program.

3.2. Effects of Helicopter Dynamics on Autorotation Transfer of Training

For a maneuver that requires a combination of rule-based and skill-based control behaviors[30], such as autorotation, training involves pilots' intimate familiarization with the inherent dynamics and handling qualities of the aircraft they are dealing with. Different handling characteristics may put a different level of workload on the pilot to accomplish the task. As a consequence, pilots will need to adjust their control strategy based on the helicopter dynamics they control.

The two quasi-transfer-of-training experiments[14,15] described in this section were conducted in the SIMONA Research Simulator (Fig. 8) at Delft University of Technology to understand whether certain types of dynamics can better prepare pilots to the variety of conditions that they may face during emergencies and provide them with a more robust and flexible control strategy that should prevent them from committing many possible errors.

Figure 8: The SIMONA Research Simulator at Delft University of Technology[31].

The basis for these experiments was set by a previous study by the authors[13], conducted also as part of NITROS ESR 12 research. This study showed that the introduction of the rotor speed degree-of-freedom in the helicopter's equation of motion to simulate autorotation, considerably affects the stability characteristics of the helicopter, thus requiring a different control strategy by the pilot than in level flight. Furthermore, the effect of variations in the *autorotative flare index*[32] on helicopter dynamics stability were investigated, showing that autorotation should not be considered only as an energy management task, as the definition of the autorotative flare index suggests. Indeed, high values of the index may also lead to degraded stability characteristics and hence a possibly more difficult autorotation.

From the wide range of helicopter configurations studied in Ref. 13, two of them proved to be considerably different in terms of handling qualities during a pre-experiment with a test pilot[14] and were selected for the two experiments described in this section[14,15]. The two configurations are characterized by a different autorotative index and a different level of intervention required by the pilot: "hard", with high pilot compensation required, and "easy", with low compensation required.

In both experiments, two groups of experienced pilots tested the two types of dynamics in a different training sequence: hard-easy-hard (HEH group) and easy-hard-easy (EHE group) (Tab. 2). Pilots had to perform a straight-in autorotation maneuver (Fig. 9), controlling a non-linear and generic helicopter model with quasi-steady flapping dynamics[33]. The two experiments were very similar, but in the first[14] a four degrees-of-freedom (3-DOF longitudinal rigid-body dynamics plus rotorspeed DOF) helicopter model was considered, whereas in the second one[15] a seven degrees-of-freedom helicopter model (6-DOF rigid-body dynamics plus rotorspeed DOF) was used.

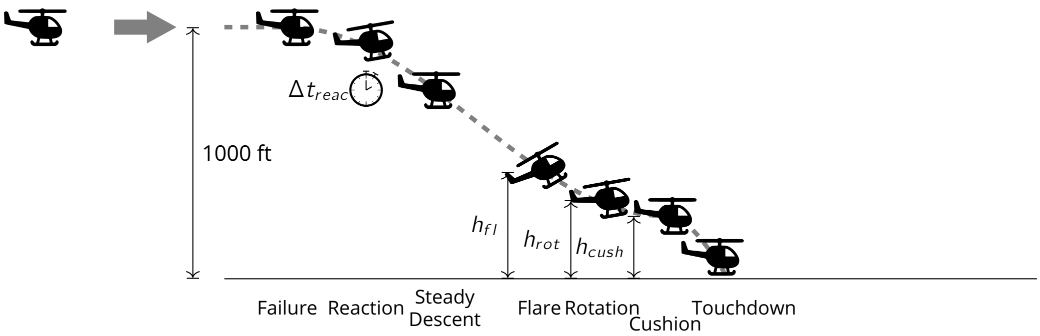
The outcome of these experiments confirm previous experimental evidence that showed positive transfer of skills from agile (hard case, where high compensation is required by the pilot) to inert (easy case, where low intervention is required by the pilot) dynamics, but not the opposite for a different training task[34]. Indeed, in both our experiments, both groups of participants exhibit a decrease in the rate of descent at touchdown from the hard to the easy dynamics, but not after a transition from the easy to the hard dynamics (Fig. 10).

In both experiments, the hard helicopter dynamics seem to foster the development of more robust and flexible flying skills. Indeed, participants of the HEH group adopted, from the start of the experiment, a control strategy similar to the one used in real helicopters, as opposed to the participants of the EHE group, who tend to underestimate the altitude during the first two phases of the experiment, thus preempting the cushion. This sometimes results in a balloon landing (the helicopter gains altitude before touchdown), causing the rotor speed to drop down and the consequent loss of collective effectiveness is counteracted by starting a second flare.

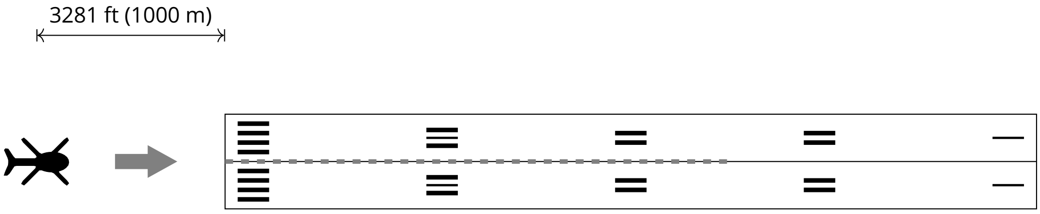
Since the final part of the autorotation is mainly a longitudinal maneuver, the use of a 3-DOF symmetrical helicopter model adopted in the first study[14] allows the collection of accurate experimental data in terms of pilots' performance at touchdown (Fig. 10) and control strategy. This is also confirmed by the fact that the participants of both groups succeeded in attaining desired performance at touchdown in the lateral-directional metrics almost in every run of each phase. However, the 3-DOF symmetrical helicopter model case fails in providing sufficient visual and motion cues to recognize the occurrence of the engine failure, due to the missing initial yaw in the direction of the rotor angular speed that follows a power failure. This is proven by the fact that the average reaction time of the participants of the first study[14] ($\approx 0.6s$) is approximately twice as high as that of the participants of the second study[15] ($\approx 0.3s$).

Table 2: Autorotation experiment phases[14,15].

Phase	HEH group	EHE group	Duration (no. of autorotative landings)	Motion
Familiarization	Hard helicopter dynamics	Easy helicopter dynamics	3	Off
Training	Hard helicopter dynamics	Easy helicopter dynamics	15	On
Transfer	Easy helicopter dynamics	Hard helicopter dynamics	15	On
Back-Transfer	Hard helicopter dynamics	Easy helicopter dynamics	15	On

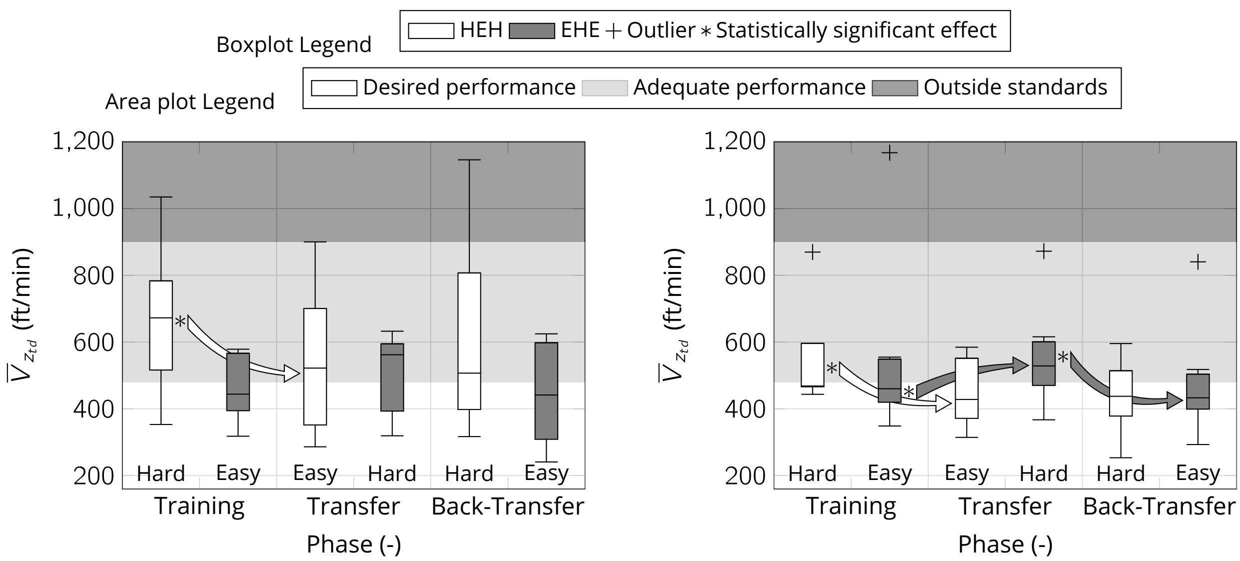


(a) Side view.



(b) Top view.

Figure 9: Suggested course for straight-in autorotation maneuver[14,15].



(a) 7-DOF study[15].

(b) 4-DOF study[14]

Figure 10: Comparison of the average rate of descent at touchdown between the two experiments[14,15].

4. CONCLUSIONS & RECOMMENDATIONS

The ever growing realm of helicopters' applications is related to helicopters' unique freedom of movement: they can hover, fly forward, sideways, backward, land and take-off vertically. Thus, they can access places otherwise inaccessible by any other mean of transportation. However, such versatility makes them intrinsically unstable and difficult to control, leading to a large chance of accidents during flight, which is partially due to the challenging applications in which helicopters are usually employed (e.g., offshore support, Helicopter Emergency Medical Services (HEMS), corporate/VIP transport, Search and Rescue (SAR), military operations, etc.). Indeed, such applications entail hostile environments and adverse environmental conditions (e.g., proximity to obstacles, Nap-of-the-Earth (NoE), low visibility, turbulence, etc.). Achieving the capability to operate helicopters safely in day/night and all weather conditions is the natural evolution of their current use. However, this safety enhancement cannot be accomplished disregarding pilots' training and the contribution that can be provided by flight simulators to both pilot training and certification.

Indeed in-flight training is expensive and potentially dangerous, therefore simulator-based training is the only viable alternative to enable pilots to extensively practice hazardous scenarios, such as engine failures. In this way, pilots can be prepared to the variety of conditions that they may face during emergencies, which requires experience and judgment in order to react promptly and avoid the many possible errors. Especially for rotorcraft, simulator usage has the potential to substantially reduce costs and risks. However, to avoid unrealistic training and negative transfer of skills when similar situations are encountered during actual flight, there is the need to bridge the gap between simulator scenarios and reality for edge-of-the-envelope flight.

The research presented in this paper was conducted as part of the European Joint Doctorate NITROS (Network for Innovative Training on Rotorcraft Safety) project and set out to investigate procedures to prevent or alleviate the occurrence of flight simulator negative transfer of training. Two different training tasks, hover and autorotation, were considered to address the needs deriving from both initial and recurrent pilot training. An approach that requires an in-depth analysis of the actual training task is adopted for both maneuvers to identify the essential aspects that need to be replicated in the simulator. Quasi-transfer-of-training experiments are then conducted to either confirm the effectiveness of the developed training program or to identify elements of the simulation that can better prepare pilots for the unexpected.

The outcome of this research yielded a number of key conclusions and recommendations concerning simulator training of helicopter pilots:

1. According to current regulations on Flight Simulator Training Devices, the ability of a flight simulator to replace or complement in-flight training is ascribed to a qualification procedure. The qualification requirements are very strict and concern both hardware (e.g., visual, motion, and control loading systems, etc.) and software (e.g., flight mechanics model of the helicopter, motion cueing algorithms, etc.) components. This process leads to highly sophisticated, complex and expensive devices, that may be more attractive to be procured, but sometimes are not fit for the specific training purpose. However, no emphasis is given on the training program (e.g., the structure and the focus should be adapted based on trainee's flight experience and on the difficulty of the task), which, on the contrary, should cover a prominent role with respect to simulator fidelity, especially during ab initio training.

2. The minimum standards for training qualification that a flight simulator should comply with depend upon the type of training demanded (*ab initio* and refresher training, type rating training with limited checking/testing capability or proficiency checks and skill tests). Likewise, also the training program needs to be tailored to the audience/trainees needs. For instance, higher-skilled learners (experienced subjects) benefit less from any load-reducing strategies during the training process than task-naïve learners (inexperienced subjects) do. Consistent with earlier work[19–21], the experiment on initial hover training showed indeed that a part-task training program is beneficial for trainees with no prior flight experience neither in actual helicopters nor in simulators, as they are able to stabilize the helicopter model after three hours of simulator training.

3. The two experiments on autorotation showed that pilots trained in high resource demanding conditions develop a more robust control technique, that can be easily adjusted according to the helicopter handling characteristics, after a short adaptation phase. This may result in a better capability to handle emergencies like engine failures in the real world, where the actual situation may easily divert from the training scenario, because they can quickly adapt

to unexpected conditions. The current simulator training syllabus for autorotation should be updated to include several configurations with different handling characteristics, which can be obtained for example considering different models of the same helicopter family, to give to the trainee the opportunity to familiarize with helicopters with different sizes, dynamics and “feel”. This can help inexperienced pilots to better understand that autorotation is not a “by-the-numbers” procedure and that adaptability and judgement of the pilot should always cover a prominent role in the accomplishment of the task.

4. Accident reports pointed out that the development of a standardized training program for autorotation and emergency aircraft handling is essential to enhance helicopter safety. Due to time and resource constraints, the effectiveness of the autorotation training program presented in Sec. 2.2 could not be assessed. However, the results of the two experiments about autorotation are promising and represent a solid foundation to further extend them, by conducting a new experiment with student pilots to obtain more evidence for the findings presented in Sec. 3.2, which are based on experienced helicopter pilots, and to further develop the proposed training program towards a new standard.

ACKNOWLEDGEMENTS

This study has been carried out in the context of the European Joint Doctorate NITROS (Network for Innovative Training on Rotorcraft Safety) project, whose main goal is to enhance rotorcraft safety by addressing critical aspects of their design. On behalf of the NITROS project, the authors would like to thank all the participants of our experiments for their efforts, as well as Prof. Heinrich H. Bülthoff and the Max Planck Institute for Biological Cybernetics for having supported the first author’s secondment to conduct the experiment on hover.

This project has received fundings from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement N° 721920.

REFERENCES

[1] G. Apostolo. *The Illustrated Encyclopedia of Helicopters*. Bonanza Books, 1984.

[2] International Helicopter Safety Team. Accident Analysis Process for a Joint Helicopter Safety Analysis Team (JHSAT). , International Helicopter Safety Team, 2012.

[3] F. D. Harris. No Accidents—That’s the Objective; The 26th Alexander A. Nikolsky Lecture. *Journal of the American Helicopter Society*, 2007.

[4] U.S. Joint Helicopter Safety Analysis Team. The Compendium Report: The U.S. JHSAT Baseline of Helicopter Accident Analysis - Volume I, 2011.

[5] U.S. Joint Helicopter Safety Analysis Team. The Compendium Report: The U.S. JHSAT Baseline of Helicopter Accident Analysis - Volume II, 2011.

[6] European Helicopter Safety Analysis Team. EHEST Analysis of 2000-2005 European Helicopter Accidents, 2010.

[7] European Helicopter Safety Analysis Team. EHEST Analysis of 2006-2010 European Helicopter Accidents, 2015.

[8] D. J. Allerton. *Principles of Flight Simulation*. 2009.

[9] E. Farmer, J. van Rooij, J. Riemersma, P. Jorna, and J. Moraal. *Handbook of Simulator-Based Training*. Routledge, 1999.

[10] P. W. Caro. Aircraft Simulators and Pilot Training. *Human Factors*, 15(6):502–509, December 1973.

[11] R. T. Hays and M. J. Singer. *Simulation Fidelity in Training System Design: Bridging the Gap Between Reality and Training*. Springer-Verlag, 175 Fifth Avenue, New York, NY 10010, USA, 1989.

[12] P. F. Scaramuzzino, G. D’Intino, S. Geluardi, M. D. Pavel, D. M. Pool, O. Stroosma, M. Mulder, and H. H. Bülthoff. Effectiveness of a Computer-Based Helicopter Trainer for Initial Hover Training. In *Proceedings of the 44th European Rotorcraft Forum (ERF 2018)*, Delft, NL, 2018.

[13] P. F. Scaramuzzino, M. D. Pavel, D. M. Pool, O. Stroosma, G. Quaranta, and M. Mulder. Investigation of the Effects of Autorotative Flare Index Variation on Helicopter Flight Dynamics in Autorotation. In *Proceedings of the 45th European Rotorcraft Forum (ERF 2019)*, Warsaw, Poland, 2019.

[14] P. F. Scaramuzzino, M. D. Pavel, D. M. Pool, O. Stroosma, M. Mulder, and G. Quaranta. Effects of Helicopter Dynamics on Autorotation Transfer of Training. *Journal of Aircraft*, (accepted for publication), 2021.

[15] P. F. Scaramuzzino, D. M. Pool, M. D. Pavel, O. Stroosma, G. Quaranta, and M. Mulder. Autorotation Transfer of Training: Effects of Helicopter Dynamics. *Aerospace Science and Technology*, (under review), 2021.

[16] J. Sweller, J. J. Van Merrienboer, and F. G. Paas. Cognitive Architecture and Instructional Design. *Educational Psychology Review*, 10(3):251–296, 1998.

[17] J. Sweller. Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction*, 4(4):295–312, jan 1994.

[18] C. D. Wickens, S. Hutchins, T. Carolan, and J. Cumming. Effectiveness of part-task training and increasing-difficulty training strategies: A meta-analysis approach. *Human Factors*, 2013.

[19] D. Fabbroni, S. Geluardi, C. A. Gerboni, M. Olivari, G. D'Intino, L. Pollini, and H. H. Bülthoff. Design of a Haptic Helicopter Trainer for Inexperienced Pilots. In *Proceedings of the AHS Annual Forum 73, Fort Worth (TX)*, pages 2097–2108, May 2017.

[20] D. Fabbroni, S. Geluardi, C. A. Gerboni, M. Olivari, L. Pollini, and H. H. Bülthoff. Quasi-Transfer-of-Training of Helicopter Trainer from Fixed-Base to Motion-Base Simulator. In *Proceedings of the 43rd European Rotorcraft Forum (ERF 2017)*, September 2017.

[21] D. Fabbroni, F. Bufalo, G. D'Intino, S. Geluardi, C. A. Gerboni, M. Olivari, L. Pollini, and H. H. Bülthoff. Transfer-of-Training: From Fixed- and Motion-base Simulators to a Light-Weight Helicopter. In *Proceedings of the AHS Annual Forum 74, Phoenix (AZ)*, May 2018.

[22] D. L. Kleinman, S. Baron, and W. H. Levison. An Optimal Control Model of Human Response, Part I: Theory and Validation. *Automatica*, 6(3): 357–369, 1970.

[23] S. Baron, D. L. Kleinman, and W. H. Levison. An Optimal Control Model of Human Response, Part II: Prediction of Human Performance in a Complex Task. *Automatica*, 6(3):371–383, 1970.

[24] S. Coyle. *The Little Book of Autorotations*. Eagle Eye Solutions, first edition, 2013.

[25] R. W. Prouty. *Helicopter Aerodynamics Volume II*. Eagle Eye Solusions, first edition, 2009.

[26] Advisory Group for Aerospace Research and Development. Fidelity of Simulation for Pilot Training. AGARD-AR-159, North Atlantic Treaty Organization, Neuilly sur Seine, France, 1980.

[27] S. Geluardi. *Identification and augmentation of a civil light helicopter: transforming helicopters into Personal Aerial Vehicles*. MPI Series in Biological Cybernetics; 47, University of Pisa and Max Planck Institute for Biological Cybernetics, 2016.

[28] S. Geluardi, F. M. Nieuwenhuizen, J. Venrooij, L. Pollini, and H. H. Bülthoff. Frequency Domain System Identification of a Robinson R44 in Hover. *Journal of the American Helicopter Society*, 63(1):1–18, January 2018.

[29] F. M. Nieuwenhuizen and H. H. Bülthoff. The MPI CyberMotion Simulator: A Novel Research Platform to Investigate Human Control Behavior. *Journal of Computing Science and Engineering*, 7(2):122–131, June 2013.

[30] J. Rasmussen. Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, smc-13 (3):257–266, May 1983.

[31] O. Stroosma, R. van Paassen, and M. Mulder. Using the SIMONA Research Simulator for Human-Machine Interaction research. In *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Austin, Texas, 2003.

[32] E. A. Fradenburgh. Technical Notes: A Simple Autorotative Flare Index. *Journal of the American Helicopter Society*, 29(3):73–74, jul 1984.

[33] P. D. Talbot, B. E. Tinling, W. A. Decker, and R. T. N. Chen. A Mathematical Model of a Single Main Rotor Helicopter for Piloted Simulation. NASA/TM-84281, 1982.

[34] H.-G. Nusseck, H. J. Teufel, F. M. Nieuwenhuizen, and H. H. Bülthoff. Learning System Dynamics: Transfer of Training in a Helicopter Hover Simulator. In *Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit*, Honolulu, Hawaii, 2008.