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Design and Evaluation of a Haptic Aid for Training of the Manual Flare Manoeuvre

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The use of haptic feedback as a tool for skill training has shown benefits for the formation of motor-memory and support for certain temporal tasks. Therefore, this research focuses on the development of a haptic aid for supporting the training of the challenging manual flare maneuver in initial pilot training. The haptic aid, which consisted of three "off-target" haptic modes each meant to clarify a typical mistake in flare execution, was designed based on instructor actions during real flight training. The High Roundout (HR) mode was designed to better train flare timing. This haptic mode implemented an increase in pitch-up stick stiffness when still above the desired flare altitude. The Late Roundout (LR) and Ballooning (BA) modes used repeated pulses on the stick – in pitch-up and pitch-down directions, respectively – to alert trainees when they flared too late (or not at all) or when overly large pitch-up inputs that would lead to regaining altitude were given. To test the haptic aid, a quasi-transfer-of-training experiment with 16 novices was performed in a full-motion research simulator. A baseline group and a group receiving haptic feedback were compared and in the haptics group the haptic aid was used during the training phase of the experiment, but disabled in the evaluation phase. A second-stage evaluation, with an untrained landing scenario, was used to verify the generalizability of the skills. The obtained data indicates no improved learning effect regarding flare trajectory. It was found that due to the difficulty of the task, strategies based on linking the cues to desired discrete touchdown performance were formed. The usage of the HR mode, however, resulted in more consistent initiation of the flare which was retained after transfer. The second-stage evaluation also did not show worsening of flare performance, suggesting generalizability of the skills with the haptic aid.

I. Introduction

Flying safely in today's highly automated and complex aircraft still implies that pilots need to rely on their basic flying skills in case of unexpected events. These basic skills form a basis for every *ab initio* pilot training program.[1] One of the maneuvers trained in the early stages of flight training is the transition from approach to touchdown, the flare maneuver. Flaring an aircraft is, due to its dynamic nature, short duration, and proximity to the ground inherently challenging and therefore one of the common stagnation points during initial training. This transition from approach to touchdown is also commonly perceived by pilots as being the most difficult maneuver occurring during normal flight.[2] On top of this, numerous aviation accidents result from an incorrectly performed landing. In fact, the last phases of flight (i.e., final approach and landing) are where most of the fatal aircraft accidents occur, i.e., 49% between 2006-2015.[3]

Training the flare maneuver is usually done in real flight by extensive touch-and-go sessions, where student pilots perform multiple landings in a short amount of time. When lack of progress is evident in this stage, this can add cost to the already expensive training. There are also some psychological aspects related to this part of training. Student pilots can become discouraged or even afraid, leading to drop outs or an increase in training time. A common mistake made by trainees who struggle with the flare is to focus too hard on their stick movements (internal focus) as opposed

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to studying the aircraft reaction to the stick movements (external focus), which leads to further disruption of learning.[4] Hence, it is important to acquire adequate landing skills in the shortest time possible, reducing the cost and minimizing the chance of dropping out of the training program.

Flight simulation training devices (FSTD) are commonly used as a tool during pilot training, as this reduces cost and risk of aircraft damage. FSTDs also have the capability to accommodate systems that are unavailable during real flight and serve as *training aids* (e.g., visual augmentation). Several of such systems have been proposed in order to train the landing. Lintern et al.[5] showed that the use of display augmentation improves the effectiveness of landing training. Le Ngoc et al. designed an enhanced synthetic vision system (SVS) based on the Jacobson flare, that helped pilots to achieve better touchdown performance. This research also showed potential as a possible training tool.[6,7] Further development of this SVS, by incorporating the change in aiming point in the beginning of the flare as proposed by Robson,[8] revealed a possible benefit in providing a standard flaring framework as such.[9] The concepts used in the above research are mainly focused on guiding the trainees towards the correct timing of the maneuver and therefore do not support the execution of the full, correct, flare trajectory (i.e., the altitude path from flare initiation to touchdown). Obtaining desired flare trajectories reduces the chance of touchdown rates being excessive and allows for better anticipation of the landing location.

The execution of the flare maneuver, is a perceptual-motor skill. This type of skill involves the interaction and integration of perceptual processes and voluntary physical movement.[10,11] By accessing one's motor-memory, a skill can be executed almost automatically, that is, with little conscious control. The formation of motor-memory is therefore crucial in the process of learning a skill as such, and can be enhanced by practice and experience.[12,13] Another way of enhancing this formation can be, by making use of haptic perception (i.e., cognitive process involving the sense of touch). Haptics are widely used in the domain of rehabilitation, where patients need to relearn simple motor tasks.[14] Generally, haptics in this area are used to enhance kinesthetic memory and therefore improve and accelerate the rehabilitation process.[15] Kinesthetic learning requires touch and movement and develops the ability of recalling timely movements for specific tasks.[16]

Haptic support can be provided in numerous forms. There is in general a distinction between passive and active support. Passive haptic systems do not generate motion of the control device (as is done by active feedback), but restrict it. An example thereof are the so-called *virtual fixtures*, a paradigm formalized by Rosenberg,[17] which highlights the boundaries of a workable domain. An example of active haptic support is haptic shared control.[18] This can be in the form of continuous guidance or in the form of bandwidth feedback (e.g., no feedback is felt when inside or outside a predefined bandwidth). Several researchers have investigated the application of either type of haptic support system. Feygin et al.[19] investigated the use of haptic guidance during training of a perceptual motor skill. The participants in this research received a preview of a trajectory which they needed to reproduce. The preview was given via haptics, visually or combined haptics and visually. It was shown that providing haptic guidance improved the temporal aspect of the task. D'Intino et al.[20] designed a 2 degrees-of-freedom haptic support system for an experiment where participants had to learn to control a dual-axes compensatory tracking task. It was found that the group using haptic runs outperformed the manual control group in the pitch axis, but not in the roll axis. Training of a slow dynamic system using haptic shared control was investigated by Honing et al.[21] In this research, giving haptic feedback did not show an increase in training performance. De Groot et al.[22] performed an experiment on lane-keeping learning using groups that received on-bandwidth haptic feedback (i.e., cues available when on the desired target), off-bandwidth haptic feedback (i.e., cues when not on target) or no haptic feedback. It was found that the augmented groups outperformed the control group during training but this difference in performance faded during retention, however, the off-target group still outperformed the on-target group and the control group during delayed retention. In aviation, haptics have been used in combination with Unmanned Aerial Vehicle (UAV)s (to increase operator awareness).[23] Also, research has been done on the automation effects of haptics in this field.[24] The use of a haptic support system for the training of a realistic flight maneuver, however, is largely unexplored.

The goal of this paper is to design and evaluate a haptic support system (i.e., a *haptic training aid*) that can be used as a training tool for the *ab initio* training of the manual landing flare. For this purpose a haptic system was designed exploiting the supporting capabilities of haptics in both determining correct flare timing and the formation of motor-memory. This is done by using off-target haptic feedback, which may lead to an improved determination of the flare initiation point and an improvement in flare trajectory. This, in turn, can lead to improved touchdown performance. To evaluate this training tool, a dedicated quasi-transfer-of-training experiment with 16 participants without prior flying experience was conducted. The experiment was performed using a Cessna Citation I model implemented in the SIMONA Research Simulator of the faculty of Aerospace Engineering at Delft University of Technology. The experiment considered two groups of participants: a baseline group and a haptics group. Both groups learned performing landings during a training phase. The training phase was followed by an evaluation phase where the haptic augmentation was removed for the haptic group, in order to be able to see and compare the transferred skills. Additionally, the effects of removing the augmentation were explicitly investigated. A second-stage evaluation was used to test the generalizability of the learned skills to a more extreme scenario. The assessment of the performed flares was done in terms of commonly-occurring flare errors, and in terms of discrete parameters such as flare initiation height, touchdown vertical speed and touchdown location.

This paper is structured as follows. A detailed explanation of the developed haptic aid can be found in Section II. The methodology of the training experiment is described in Section III. The obtained results and corresponding discussion are presented in Sections IV and V, respectively. The paper ends with the main conclusions in Section VI.

II. Haptic Aid for Flare Training

This section will first explain the flare maneuver, followed by general methods currently used by instructor pilots to train the manual landing flare. This will form the basis on which the haptic training aid is designed.

II.A. The Landing Flare

The flare is the part where the aircraft transits from a descending approach to an attitude that allows the aircraft to stall just above the runway.[25] In this way, the vertical speed decreases to a desirable touchdown rate. In general, the flare is a very fast and short-duration maneuver. To be able to properly initiate the flare, the aircraft should be in a correct attitude (i.e., wings level, perfectly trimmed). This is most often the result of a stabilized approach where only small power and small pitch corrections are made, hence, this forms an important basis of the landing phase. In general, and especially if no crosswind is assumed (as done in this research), the longitudinal control of the aircraft is critical. Therefore, our designed haptic feedback also focuses on control in the pitch axis, i.e., fore-aft stick or column inputs.

II.B. Flare Training

Guidelines for flight training are provided to instructor pilots by the aviation authorities (e.g., EASA).[26] These guidelines, however, are very broad and general. Additionally, there is a vast variation in situations, responses of students and instructor experiences possible. There is no such thing as *the* perfect flare and, in fact, a variety in flare methods is accepted (e.g., pilots show variation in the moment where the power is set to idle). All of this leads to a lack of a predefined or "optimal" way as instructor to react on faulty actions. However, some general concepts for instructors exist.[27] In any case, safety should never be jeopardized, but in general the idea is to let the student fly as long as possible. Sometimes letting the student make a mistake is preferred over intervening. This is to increase skill learning and to enhance the learning moment. Often instructors do prohibit or restrict motion of the control device (i.e., restrict a downward pitching motion) by impeding movement in the prohibited direction. Otherwise said, taking full control as an instructor (even though the student can feel the motion) is often avoided until deemed necessary for safety.

One of the critical aspects for inexperienced pilots to master is the correct timing (i.e., commencing the flare at the correct altitude). Jacobson[7] describes this problem in the way pilots state the point to initiate the flare, they generally use a term similar as "about here". When starting to flare too early, the airspeed will decrease while the aircraft is still too high, which can lead to a stall with too much excess height resulting in damage. This is called a high roundout (see Figure 1a). Other common mistakes regarding flare trajectory include, starting to flare either too late or not at all, and pitching up too rapidly or too aggressively (see Figures 1b and 1c, respectively). These mistakes can lead to touchdown with an excessive vertical speed (i.e., damaging the aircraft or injure passengers and crew) or a regaining of altitude with a possibility of stalling too high above the runway, respectively.[28] A good flare trajectory combined with a stable approach increases the chances of obtaining desired touchdown performance, that is, a good touchdown rate and correct touchdown location.

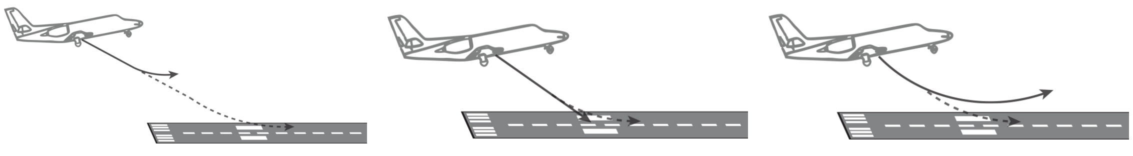
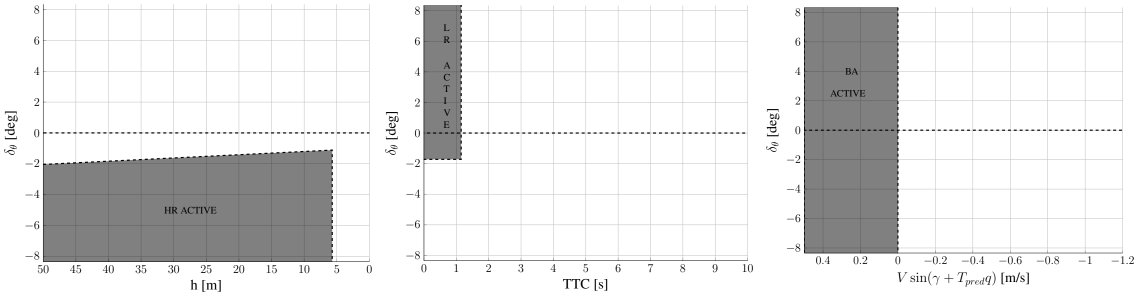

(a) High Roundout (HR) (b) Late Roundout (LR) (c) Ballooning Flare (BA)

Figure 1. Overview of the three common mistakes made during the flare maneuver. The solid line shows the trajectory representative for each mistakes.

II.C. Haptic Feedback Design

The current approach to flare training described in Section II.B forms the framework that is used to design the haptic feedback. Our approach to design of the haptic training aid focused on providing *off-target* haptic feedback, which is only active when one of the mistakes described in Section II.B is made, much like a flight instructor would do. This resulted in several haptic modes that, when activated, provide tangible feedback. This allows for the pilots to have freedom to actively control, make mistakes, and learn from them. Another reason to give feedback based on mistakes is because humans process augmented information related to erroneous performance better, as it does not interfere with the information that is perceived when a correct action is performed.[29] Schmidt and Lee[30] confirm this by stating that actively performing a motor skill enhances learning in contrast with the passive counterpart as the latter is less supportive in creating mental models of the to be performed task. Several transfer-of-training experiments show superior results when augmented cues were given only when being outside of a pre-defined boundary.[22,31] Another way of providing haptics would be to give active haptic guidance along an example trajectory. This would lead to training of only one specific flare trajectory and it would be in conflict with the idea of giving students freedom to actively control and make mistakes. This is supported by the experiment performed by O'Malley et al.,[32] which showed that using such continuous haptic feedback does not effectively support learning.



(a) Stick Deflection vs. h

(b) Stick Deflection vs. TTC

(c) Stick Deflection vs. $\dot{h}_{pred}$

Figure 2. These figures depict the zones for a 3 deg glideslope case, where the modes are active (HR-LR-BA). h is the height, TTC is the time-to-contact, and $\dot{h}_{pred}$ is the predicted vertical speed.

II.C.1. High Roundout Mode

If student pilots flare too early, the excess height is a risk. Hence, to indicate the point from which flare initiation is allowed, the so-called High Roundout mode (HR) was created. A "soft limit" on the stick deflection in pitch up direction was defined above a pre-defined altitude. When this boundary is crossed, an increase in stiffness is felt, which is in concurrence with instructors sometimes creating physical boundaries by restricting column movement. Figure 2a shows this boundary, creating a zone where the increase in stiffness is present. The corresponding force-position diagram is given by Figure 3. The point where the stiffness increases is denoted by $\delta_{\theta bound}(h)$. This point shifts in the direction of the origin when the height above the ground surface decreases. The dashed line corresponds to the case when the aircraft is below the pre-defined altitude. In order to reduce the chance of providing confusing feedback, the stiffness increase does not reappear once the aircraft reached an altitude below the pre-defined altitude (e.g., in case of an increase in altitude).

For the HR mode, the relation used to calculate the force-displacement characteristic, i.e., the force (F) necessary to obtain a certain stick deflection δ_θ, is given by:

$$F = \begin{cases} k_{inh}\delta_\theta & \text{if } \delta_\theta \geq \delta_{\theta bound}(h) \\ k_{inh}\delta_\theta + \boldsymbol{k_{viol}}(\delta_\theta - \delta_{\theta \mathrm{bound}}(\mathrm{h})) & \text{if } \delta_\theta < \delta_{\theta bound}(h) \end{cases} \quad (1)$$

where k_{viol} is the added haptic feedback stiffness (see Figure 3), k_{inh} the inherent stiffness of the side-stick, and h the aircraft altitude.

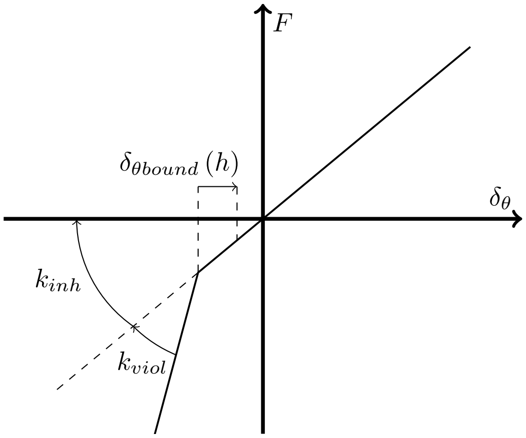


Figure 3. Force vs. stick deflection, the arrow depicts the shift of $\delta_{\theta bound}(h)$ when the height decreases.

II.C.2. Late Roundout Mode

Flaring too late or not at all can result in dangerously high touchdown rates. To signal an imminent late flare, a Late Roundout (LR) haptic mode was designed. This mode is activated when the Time To Contact (TTC) is lower than a specified value and there is no deflection of the stick in the pitch-up direction. The TTC is defined as:[33]

$$TTC = \frac{h}{\dot{h}} \tag{2}$$

where, h is the altitude and $\dot{h}$ is the vertical speed.

Figure 2b shows the defined zone that will, when entered, trigger the haptic mode. The alerting feedback was chosen to be a repeated pulse in the pitch-up direction. An additional restriction on the feedback is set by not activating this mode when the vertical velocity is below a pre-determined value (i.e., the maximum allowed touchdown rate). To reduce the number of pulses, to avoid continuous activation of the haptic signaling, this mode was allowed to only activate once, preventing multiple successive instances of LR triggering. This could happen if during landing the LR is triggered followed by a too large stick deflection leading to a regain in altitude, again followed by a LR triggering. In this situation the repeated pulse is thus only given once at the beginning.

II.C.3. Ballooning Mode

The last haptic mode is called the Ballooning mode (BA). When a pilot initiates the flare, but pitches too hard, the aircraft will cease to descend and, being in ground effect, might even climb. Therefore, this mode is designed to trigger when entering the marked zone in Figure 2c. Here, the predicted vertical speed $\dot{h}_{pred}$ has a value equal to or greater than 0 m/s (i.e., flying level or climbing). The predicted vertical speed is defined as:

$$\dot{h}_{pred} = V \sin(\gamma + T_{pred} q) \tag{3}$$

where γ is the flight path angle, q is the pitch rate, V is the airspeed and T_{pred} is the prediction time. When a ballooning flare occurs, a set of repeated alerting pulses are given in the pitch down direction, so in the opposite direction of the LR pulses.

II.D. Haptic Feedback Tuning

For tuning the haptic modes, data was analyzed from previous research. This data corresponds to landings made in the same research simulator using the same non-linear Cessna Citation I model.[9]

II.D.1. High Roundout Mode Tuning

The boundary $\delta_{\theta bound}(h)$ (see Eq. (1)) was determined by using control activity in the performed approaches. This was used to obtain a limit that allows more freedom at higher altitudes (in the beginning of the final approach phase) as to give the ability to recover from a deviation from the glideslope (see Figure 2a). Yet, a limited amount of freedom is necessary during the whole approach to be able to cope with turbulence perturbations. The added stiffness k_{viol} was chosen empirically to be clearly notable, but weak enough to be overruled if desired (i.e., pitch-up inputs were always possible). k_{inh} was determined to be 0.75 N/deg. Table 1 gives all the relevant values and parameters used for this research. The height where the added stiffness disappears is determined based on the height stated in the Pilot Operating Handbook (POH) of the Cessna Citation I, which is 15ft ($\approx$ 4.6 m). A small addition (1.1 m), based on the vertical speed and human reaction time, was used to prevent the stiffness from disappearing at the exact same moment the flare should be initiated. When a non-standard glideslope is used during approach (i.e., different approach vertical speed), the optimal flare initiation height and thus the feedback settings change. Appendix A gives a more detailed explanation on this matter.

Table 1. Haptic feedback parameters and their values for each designed haptic mode.

Mode	State	Bound (3°)	Bound (4°)	Extra Parameter	Value
HR	h	5.7 m	6.4 m	$\mathrm{k_{viol}}$	5 N/deg
LR	TTC	1.15 s	1.35 s	n/a	n/a
	$\dot{\mathrm{h}}$	-1.3 m/s	-1.3 m/s	n/a	n/a
BA	$\dot{\mathrm{h}}_{\mathrm{pred}}$	0.0 m/s	0.0 m/s	$\mathrm{T_{pred}}$	0.40 s

II.D.2. Late Roundout Mode Tuning

From vertical deceleration profiles during the flare, obtained from a previous experiment,[9] the minimum time needed to go from approach to touchdown was determined. The average value was found to be 1.73 s and would correspond to the critical TTC for activation of the LR mode. This obtained value was tested and it was found that a decrease was needed (i.e., to 1.15 s), however, to allow for sufficient free control space between the HR mode and the LR mode activation regions. The limit vertical speed for the LR mode was set to 1.3 m/s as this is the maximum allowed touchdown rate for the Cessna Citation I. Table 1 gives a summary of these values. A distinction was made for different glideslope angles, Appendix A provides more detail on this difference. Table 2 gives the parameters used for the repeated pulses. Repeated pulses tend to have a high perceived authority and care must be taken not to induce too large deflections. Also due to the short duration of the flare maneuver, it can be that a lot of feedback is given in a short amount of time, reducing its intuitiveness. The parameters related to the pulses were determined empirically.

Table 2. Repeated haptic pulse feedback parameters

Mode	Pulse Period	Pulse Width	Pulse Start	Magnitude	Direction
LR	0.75 s	0.25 s	0.01 s	10.0 N	Pitch Up
BA	0.75 s	0.25 s	0.01 s	7.5 N	Pitch Down

II.D.3. Ballooning Mode Tuning

An initial value of the BA mode prediction time constant T_{pred} was chosen by computing and comparing the predicted vertical speed for several normal and ballooning landings from the experiment of Ref. 9. Several values for T_{pred} were chosen and the resulting predicted vertical speeds were compared with the defined zone (see Figure 2c). The final value (see Table 1) was obtained empirically. By changing this value, a change of sensitivity of the triggering of the mode is obtained. The parameters related to the pulses accompanying this mode can be found in Table 2. The parameters related to the pulses, again, were determined empirically.

III. Methodology

III.A. Experimental Set-Up

A quasi-transfer-of-training human-in-the-loop experiment was performed to test the effectiveness of the designed haptic training aid, as described in Section II, for initial flare training. The experiment set-up is similar to that used in a previously conducted landing training experiment.[9] The research was performed at the faculty of Aerospace Engineering at Delft University of Technology using the full-motion SIMONA Research Simulator.[34] Motion cueing was available throughout the whole experiment, adding realism (see Table 3 for the motion filter settings). A non-linear Cessna Citation I aircraft model was used. Subjects had control over the throttle, the pitch and roll axis but no directional control (yawing) was possible. A control-loaded 2 degrees-of-freedom electrical Moog FCS Ecol-8000 side-stick located on the right-hand side of the cockpit was used for giving the control inputs. The experiment consisted of several runs, each containing a landing scenario. Every scenario started with the final approach phase followed by the performance of the flare. At the beginning of the run, the aircraft was perfectly trimmed, making sure no additional throttle changes were necessary in the final approach. Turbulence was used to increase realism and to stimulate active controlling, but no wind was present.

Table 3. Motion filter settings, K is the filter gain, ω_n is the break frequency, ζ_n is the damping ratio and ω_b is the third-order break frequency.

DOF	$\mathbf{K}[-]$	$\omega_\mathbf{n}[\mathbf{rad/s}]$	$\zeta_\mathbf{n}[-]$	$\omega_\mathbf{b}[\mathbf{rad/s}]$	**Order** [-]
Heave	0.5	2.0	0.7	0.2	3
Surge	0.5	1.0	0.7	0.0	2
Sway	0.5	1.0	0.7	0.0	2
Pitch	0.5	0.8	0.7	0.0	2
Roll	0.5	0.8	0.7	0.0	2
Yaw	0.5	0.8	0.7	0.0	2

Scenarios differed in terms of approach angle and runway width. Pilots can use the runway width angle (ψ) (i.e., the angle between the left and right edges of the runway at the aiming line) to determine the flare initiation height.[35,36] Hence, changing the approach angle (and therefore the approach vertical speed) and the runway layout, changes the perception of this angle. This allows for the generalization the acquired skills of trainees. Different start distances were also used to avoid the use of undesired cues (e.g., counting the duration of a run). Figure 4 shows the tested landing scenarios, with the considered standard ICAO runway widths highlighted and the solid line indicating the standard 3 deg approach angle.[37] An extreme condition was defined using a 4 deg glideslope angle, combined with a narrow runway width of 18 m, to assess the generalizability of the skills.

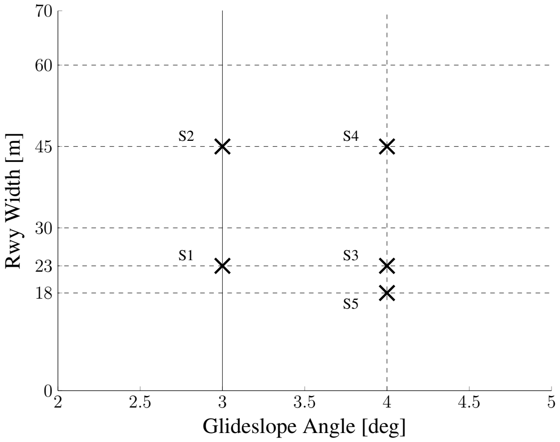


Figure 4. Overview of the tested landing configurations. The crosses are the selected scenarios (S), the ICAO standard runway widths are indicated with the dashed lines as well as the non-standard 4° glideslope angle. The solid line corresponds to the standard 3° approach angle. S1, S2, S3 and S4 are used for the training phase and the first evaluation phase. S5 is the extreme condition used in the second evaluation phase.

III.B. Participants

To test the effect of the haptic aid as described in Section II on flare training, a quasi-transfer-of-training human-in-the-loop experiment with 16 participants (15 male, 1 female) was conducted. The participants (ages 24±2.42 years) were all students at Delft University of Technology and signed a consent form prior to the experiment, confirming their voluntary participation as well as their lack of prior flight experience. They also confirmed being right-handed, this is due to the side-stick being on the right hand side of the cockpit. The baseline group (without any augmentation) was shared with a similar quasi-transfer-of-training landing experiment.[9] The subjects that formed the haptics group (with haptic augmentation) were chosen to form balanced groups. In order to do this, the approach performance of the familiarization runs were used (see Section III.C.1). A written experiment briefing was received one day before the start of the tests. The briefing contained information regarding the experiment procedures and the actions required to flare an aircraft. Subjects were instructed to look outside of the cockpit during approach and landing, to keep the pitch variations to a minimum, to pay attention not to over-pitch in order to prevent a tailstrike and to perform the following actions when they thought the start of the flare was to be initiated:

1. Reduce power to idle,
2. Relocate the viewpoint from the aimpoint towards the far end of the runway, and
3. Gently pull back the side-stick in order to pitch-up and reduce the vertical speed of the aircraft.

The haptics group received additional information regarding the haptic feedback. The briefing stated that such feedback would be available throughout the training phase of the experiment. It was also explicitly explained that when a good flare is performed no haptic feedback should be felt.

III.C. Experimental Procedure

The experiment was divided into three main parts (see Figure 5). Firstly there was the familiarization phase, followed by a training phase and ending with the evaluation phase. In the formation of motor-memory, consolidation is a crucial part where post-practice neuronal processes take place, stabilizing the memory. To increase the retention (i.e., the time between the end of the acquisition phase and the recalling of a memory), maximizing this consolidation, the experiment was performed on two consecutive days with a period of 24 hours in between.[13,38] The familiarization and the first part of the training phase were performed on the first day, the second part of the training and the evaluation were done on the second day. A block contained four runs, except the last block which contained all 10 runs of the extreme condition. The first two blocks are called the beginning of the training phase (T1), the last two blocks of this phase denote the end of the training phase (T2). The first evaluation phase (E1) comprises of Blocks 11 and 12.

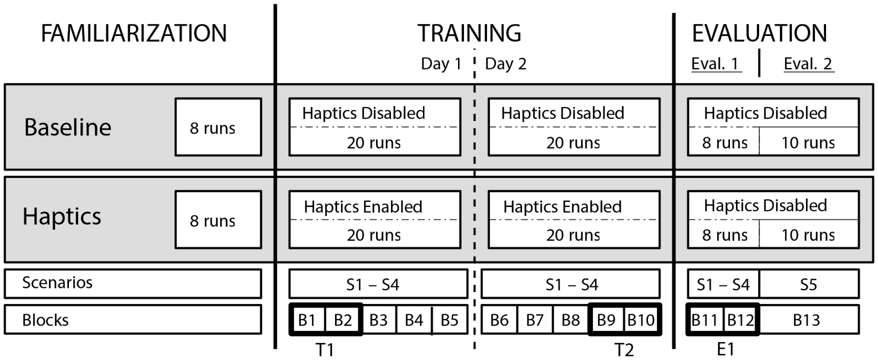
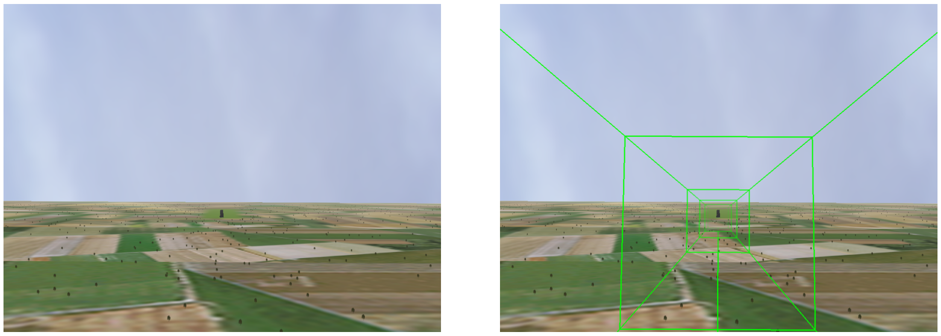


Figure 5. Overview of the experiment for both the baseline group and the haptics group.

III.C.1. Familiarization Phase

The experiment started with two runs to get the participant acquainted with the simulator, the controls and aircraft dynamics. For the very first run, the motion was disabled, from the second run onwards the motion was always enabled throughout the whole experiment. The runs started 1,000 ft Above Ground Level (AGL) in landing configuration trimmed for a free flight scenario.

As described in Section II.B, for good flare performance flying a stable approach is of the utmost importance. Therefore, the acquaintance runs were followed by six runs designed to train participants in flying the approach. Starting at 1,000 ft AGL, they flew a descent to 60 ft AGL, where the simulation was stopped before the initiation of the flare. While the main experiment only used regular out-of-the-window visuals, see Figure 6a, the first three approaches included a tunnel-in-the-sky[39] to guide the participants along the desired glideslope as shown in Figure 6b. This tunnel was removed for the last three runs of the familiarization phase. In order to get balanced groups, the familiarization runs were used as a first performance metric. For each approach the Root Mean Square (RMS) of both the lateral and vertical glideslope tracking errors was calculated. At the end of each run, the subjects were informed of their lateral and vertical error RMS to allow learning.



(a) Outside Visuals **(b) Tunnel-in-the-sky**

Figure 6. Illustration of the out-of-the-window visuals used in the experiment.

III.C.2. Training Phase

The training runs started with the aircraft on close final approach (i.e., between 70 m and 110 m AGL, dependent on the scenario) in a trimmed condition. The scenarios (S1-S4) differed as shown in Figure 4. To prevent recognition, different start positions along the glideslope were used for the same scenario. On the first day five blocks of the four scenarios were flown. The second day, another set of five blocks were performed as part of the training, resulting in a total of 40 runs for training. Every run was automatically stopped after 400 m of rollout. Every subject received the exact same order of runs as to be able to fully compare the progress between subjects on an individual run basis (i.e., to make sure differences in data are not due to different training order). During this phase, the haptics group received haptic feedback and were asked to state the feedback they perceived, after every run. The experimenter provided all subjects with performance feedback after every landing: whether their touchdown location and touchdown rate were in the desired zone, or not.

III.C.3. Evaluation Phase

In the evaluation phase, the haptic feedback for the haptics group was disabled. At the beginning of this phase they were notified of this change. Firstly, two blocks (eight runs) of the same scenarios as in the training phase were provided. After this, 10 runs of an extreme condition (S5) were performed. This extreme condition was included to test the desired generalizability of landing skills. Extreme, in this case, means that the condition was not provided during the previous phases. For this purpose the non-standard 4 deg approach angle in combination with a narrow runway (18 m width) was used.

III.D. Data Analysis

III.D.1. Independent Variables

The experiment was set-up to have one within-subjects Independent Variable (IV) and one between-subjects IV. The haptics being either enabled (haptics group) or disabled (baseline group) is the between-subjects IV.

The within-participants IV was the phase in the experiment (i.e., the moment in time). For data analysis, flare performance over the first two blocks of the training (T1), the last two blocks of the training (T2) and the first two evaluation blocks (E1) will be compared. These phases are highlighted in Figure 5. In this way the training progress can be compared, as well as the performance after transfer. The evaluation phase would reveal any undesired dependencies of the learned skills on the haptic augmentation.

III.D.2. Dependent Variables

For the Dependent Variables (DV) a distinction is made between discrete performance measures (i.e., flare initiation height, touchdown rate and location) and performance regarding the flare trajectory (i.e., occurrence of common mistakes).

The start of the flare was determined by estimating the flare initiation height,[40] using the method described in Appendix B. A distinction is made between approaches done with a glideslope angle of 3 deg and a glideslope angle of 4 deg. Other performance parameters are linked to the touchdown. The touchdown rate when the main wheels touched the runway was determined. A lower limit on this metric was set at -0.3 m/s as it is desired to make a so-called firm touchdown. This is in order to have maximum braking capability from the very beginning of the rollout phase. Firm touchdowns also prevent aquaplaning should the runway be wet. A maximum bound was set at -1.3 m/s to prevent aircraft damage. The touchdown location was characterized by the distance from the centerline laterally and the distance on the runway. Figure 7 shows the ideal location on the runway and the respective distances. The limiting values for these metrics were obtained from literature.[41–44] The percentage of successful landings (i.e., touchdown rate within limits and touchdown location within the desired region) was also calculated.

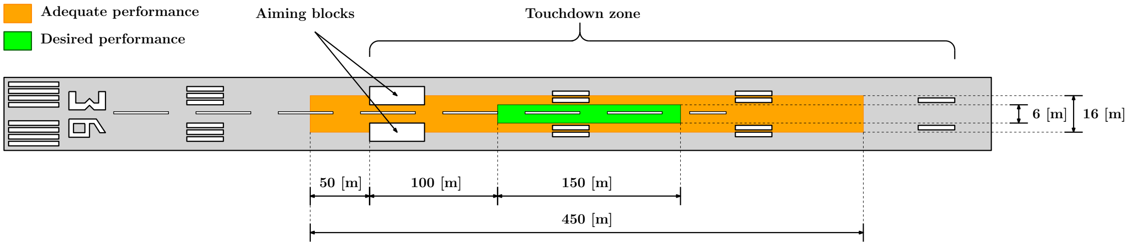


Figure 7. Definition of the touchdown location performance criteria.[9]

When obtaining a good flare trajectory, the chances of hard touchdown rates, overshoots or stalls too high above the runway reduce. However, a flare containing a mistake such as ballooning (i.e., resulting in a faulty flare trajectory) can still have adequate or even desired discrete performance measures. Therefore, it is important to look at the entire flare trajectory. The metrics used for this are the number of occurring haptic mode activations (HR, LR, BA) (see Section II). Note that these were also calculated for the data from the baseline group, without actually providing the activated feedback in the experiment. The percentage of occurrence for ballooning flares and late roundouts will be calculated separately, as well as the percentage of occurrence of both mistakes happening in the same run.

III.D.3. Statistical Methods

Statistics will be performed mainly to look for training effects, transfer-of-training effects and differences between groups. For this purpose, data from the first two training blocks (T1) will be averaged for each subject. The same is done for the last 2 training blocks (T2) and for the first two evaluation blocks (E1). The first step in the analysis will be a normality test to test the distribution of the metric (Kolmogorov-Smirnov or Shapiro-Wilk test). If no normal distribution is assumed, non-parametric statistical tests will be used. As the nature of the experiment gives both a between-subjects and a within-subject independent variable, a mixed design Analysis of Variance (ANOVA), will be used, for assumed normality. The within-subject IV has 3 levels, the beginning of training, the end of training and the evaluation. This variable will be called "phase". Given the 3 levels, Mauchly's sphericity test needs to be performed to identify equality of variances. The results of the ANOVA allow to determine the statistical difference in phase (T1-T2-E1), the interaction of the phases and groups (phase×group) and the difference between groups (baseline-haptics). Paired t-tests will be used if necessary to investigate difference between the three levels of phase within a specific group. A significance level of $\alpha = 0.05$ is chosen.

III.E. Hypotheses

For the experiment, three main hypotheses regarding training with the haptic aid were formulated:

H1: *Flare trajectory training effectiveness:* Providing active haptic aid as described in Section II during training results in faster reduction in occurrence of common mistakes regarding flare trajectory (i.e., a ballooning flare, a late roundout). This is due to a haptic feedback avoidance strategy that is adopted during training.

H2: *Discrete performance training improvement:* As a result of the improvement of the training regarding desired flare trajectories, the discrete touchdown parameters will improve (i.e., touchdown rate and touchdown location). Providing passive haptic aid as described in Section II will result in an improved learning effect regarding the flare initiation height.

H3: *Transfer-of-training effect:* It is hypothesized that due to the *off-target* nature of the feedback (i.e., only feedback is felt when making a mistake) there will be no dependency created on the cues by the haptics group. Hence, the attained level of performance will be retained during the evaluation phase. Also, the generalizability of the training should prevent performance reduction in the last phase of the evaluation (S5).

IV. Results

IV.A. Experiment Group Balance

The performance during approaches in the familiarization phase was used to make a quantitative estimate of the initial skill levels of all participants. To ensure balanced groups and thus a valid between-group comparison, an equivalent skill level and a sample of comparable subjects in both groups is required. The RMS value of the lateral and vertical offset from an ideal glideslope were used for this comparison. Table 4 shows the obtained values per subject averaged for the performed runs (i.e. 6 approaches). A test of normality showed that an independent t-test could be performed on both RMS errors. This test showed no significant difference between the groups ($RMS(e)_{vert}$ $t(14) = -1.00$ $p \geq 0.05$, $RMS(e)_{lat}$ $t(14) = -1.07$ $p \geq 0.05$).

Table 4. Familiarization phase tunnel tracking performance per subject for both experiment groups. The group means and standard deviations are also given for both RMS errors.

Baseline Group			*Haptics Group*		
Subjects	$\mathbf{RMS(e)_{vert}[m]}$	$\mathbf{RMS(e)_{lat}[m]}$	**Subjects**	$\mathbf{RMS(e)_{vert}[m]}$	$\mathbf{RMS(e)_{lat}[m]}$
BS1	7.04	10.92	HS1	7.34	5.23
BS2	6.44	5.56	HS2	7.72	11.30
BS3	6.91	8.67	HS3	7.79	7.72
BS4	5.00	4.73	HS4	4.99	7.70
BS5	7.04	12.62	HS5	6.30	9.84
BS6	2.55	4.68	HS6	3.64	3.77
BS7	5.55	3.45	HS7	10.51	10.55
BS8	5.74	2.96	HS8	5.36	11.37
mean±σ	5.78±1.51	6.70±3.60	mean±σ	6.71±2.12	8.44±2.84

IV.B. Flare Trajectory Performance

For the flare trajectory performance, the number of High Roundout (HR) counts, the percentage of occurrence of ballooning flares (BA) and late roundouts (LR) is calculated. In other words, the amount of haptic mode activations (for the baseline group, these activations are fictitious and calculated a posteriori) is counted. An extra differentiation is made for flares that contain both mistakes. The data are presented as averages per experiment block (4 runs).

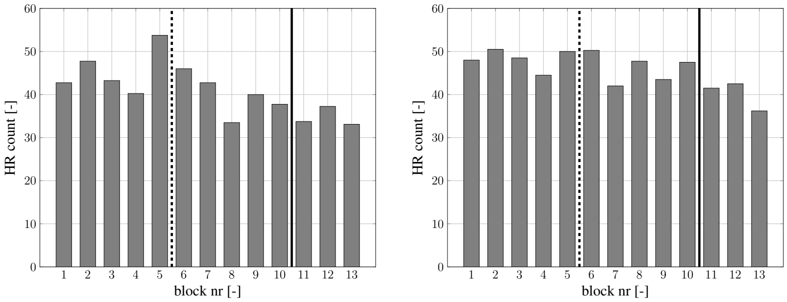
IV.B.1. High Roundout

Figure 8 gives the high roundout count for both the Baseline and Haptics group. These values are obtained by summing the number of boundary (on the stick deflection) crossings per block and dividing this by the number of runs in a block. This was done to be able to compare every phase in the experiment (i.e., the last block contains more runs). Care must be taken while interpreting this data. Due to turbulence or deviation corrections, subjects might have crossed the boundary (although very briefly). This explains the relatively large obtained HR counts. The baseline group shows a decreasing trend on the second day. The haptics group shows to be more consistent throughout the training. In the evaluation phase this latter group has the smallest number of boundary crossings (36) in the extreme condition (Block 13). It should be noted that the main effect of the High Roundout mode can be seen in the flare initiation height (discussed in Section IV.C).

A mixed-design ANOVA showed no significant difference between phases ($F(1.2,) = 1.42$ $p \geq 0.05$, Greenhouse-Geisser). Also no significant interaction effects ($F(1.2) = 0.043$ $p \geq 0.05$, Greenhouse-Geisser) nor between subject differences were found ($F(1,14) = 0.232$ $p \geq 0.05$). Due to the non-normal distribution of three of the six samples, this statistical method has a decrease in reliability. Figure 8 confirms these results.

IV.B.2. Late Roundout

Figures 9a and 9d show the percentage of occurence of the late roundout per block in the baseline and haptics groups, respectively. By looking at both figures it can be seen that the number of mode activations remains approximately



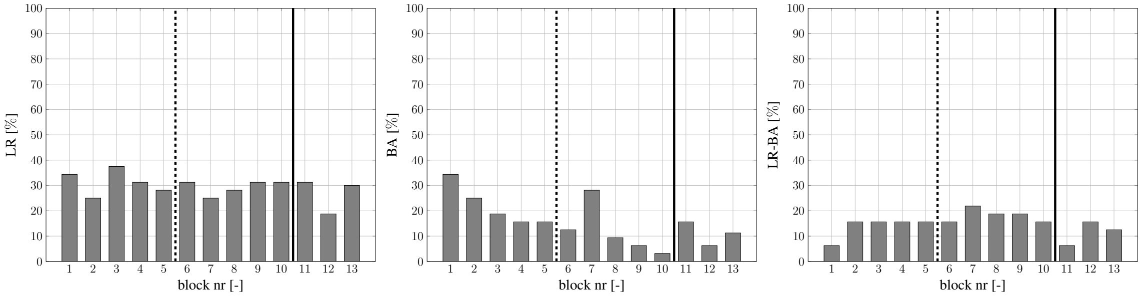
(a) Baseline Group

(b) Haptics Group

Figure 8. High Roundout count, these values are obtained by dividing the total summation per block by the number of runs in the corresponding block. The training phase and evaluation phase are separated by the solid line. The dashed line highlights the separation of day 1 and day 2.

constant during the training phase. After the transfer, for the first part of the evaluation the haptics group shows fewer late roundouts while the LR count for the baseline group remains somewhat constant. The same can be said for the second part of the evaluation of the non-augmented group. For the haptics group the LR percentage increases (16%) again compared with the first part of the evaluation. An increase in number of flares being initiated too late in this extreme condition can be explained by the narrow runway width (18 m) and the non-standard glideslope angle (4 deg). This condition results in an optical effect such that pilots tend to have the impression of being too high and hence flare too late. The higher approach angle results in an increase in approach vertical speed. The average values for the training and evaluation for the baseline are 30% and 27%, respectively. For the haptics group, the respective averages are 22% for training and 18% for evaluation.

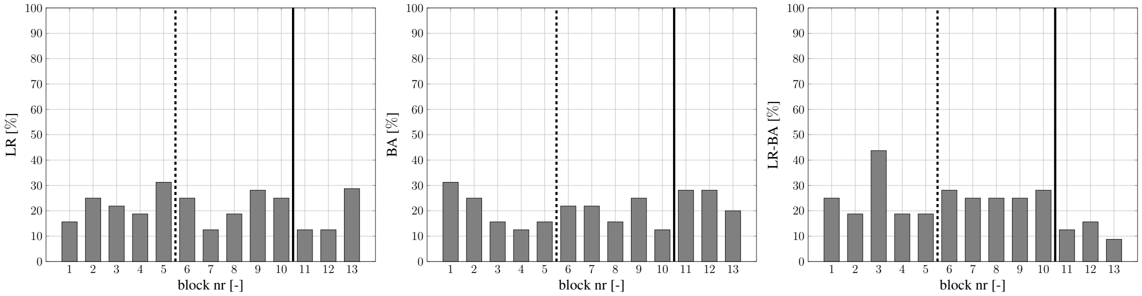
The performed mixed within-between subjects ANOVA showed no significant difference between phases ($F(2, 28) = 1.398$ $p \geq 0.05$, sphericity assumed). Also no significant interaction effects ($F(2) = 0.206$ $p \geq 0.05$, sphericity assumed) nor between subject differences were found ($F(1, 14) = 1.342$ $p \geq 0.05$).



(a) Baseline Group LR

(b) Baseline Group BA

(c) Baseline Group LR-BA



(d) Haptics Group LR

(e) Haptics Group BA

(f) Haptics Group LR-BA

Figure 9. Percentage of occurrence for ballooning flares, late roundouts and the combination thereof. The training phase and evaluation phase are separated by the solid line. The dashed line highlights the separation of day 1 and day 2.

IV.B.3. Ballooning

Figures 9b and 9e present the percentage of ballooning flares per block. A clear training effect is visible for the baseline group by the decreasing trend throughout the training. An increase is noted in the evaluation phase but the difference between the first and second part of this phase is minimal. The average BA occurrence in the training phase is 17% and 11% in the evaluation phase. For the haptics group one can see a clear training effect on the first day (first 5 blocks) but from the second day onwards the occurence is somewhat constant, an increase is also noted in the evaluation phase. The averages for the training and evaluation phases for the haptic group are 20% and 25%, respectively.

The mixed design ANOVA revealed no interaction ($F(2) = 2.333\ p \geq 0.05$, sphericity assumed) between the phase and the groups, and no significant difference between the groups ($F(1, 14) = 1.681\ p \geq 0.05$). However, there was a significant difference found for the phases ($F(2, 28) = 6.849\ p < 0.05$, sphericity assumed). A paired t-test showed a significant difference between the beginning and the end of the training of the baseline group ($t(7) = 4.32\ p < 0.05$). This is in concurrence with the data displayed in Figure 9b. No other significant differences in phase (T1,T2,E1), were found.

IV.B.4. Combined Ballooning and Late Roundout

The late roundout occurrences combined with ballooning flares are shown per block by Figures 9c and 9f. For the baseline group the training phase shows to be very consistent. The same can be said about the haptics group (although block 3 is an exception). However, the transfer marks a difference for this latter group. In the evaluation phase the percentage of LR-BA occurrence decreases. This difference, however, is not significant. The mixed design ANOVA showed no significance for the phase ($F(1.38, 19.36) = 1.151\ p \geq 0.05$, Greenhouse-Geisser). The test also showed no significant difference for either the interaction ($F(1.38) = 0.222\ p \geq 0.05$) or for the groups ($F(1, 14) = 1.065\ p \geq 0.05$). The averages of the training phase and evaluation phase are 16% and 11% for the baseline group and 26% and 12% for the haptics group.

IV.C. Discrete Flare Performance

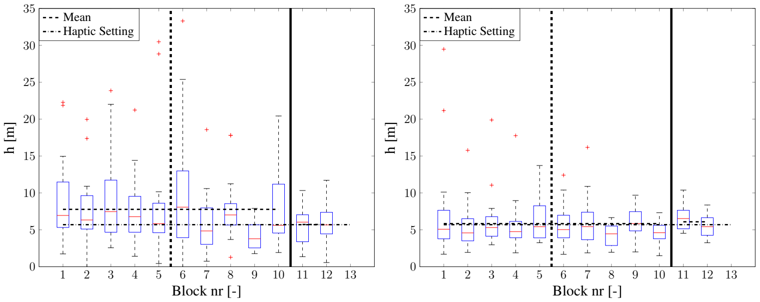
IV.C.1. Flare Initiation Height

For the flare initiation height a distinction is made between 3 deg and 4 deg glideslope approaches. The data are presented in Figure 10 which shows the flare initiation heights averaged per block for each subject, and for all subjects combined in a boxplot. Note that the second part of the evaluation (block 13) only considers the higher non-standard glideslope angle. Hence, Figures 10a and 10b do not contain data for this block. The heights where the stiffness increase disappeared (and hence the flare should be initiated) is also given in Figure 10. These heights are 5.7 m (3 deg) and 6.4 m (4 deg) as stated in Table 1.

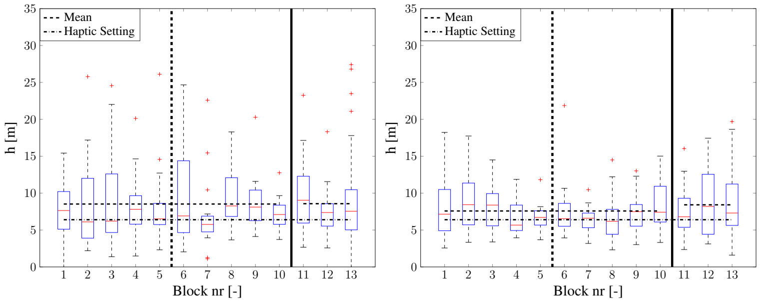
The training phase of the baseline group (3 deg) shows notable spread with the majority of outliers occurring in day 1 (see Figure 10a). There is no notable difference between the beginning of this phase and the end (although block 9 does show a set of lower values). In the evaluation phase the spread is reduced and outliers are present for a 4 deg glideslope. The average flare initiation heights in both phases are 7.8 m (training) and 5.7 m (evaluation), hence a decrease is observed. Note that this group shows low values (the boxplot in Block 6 extends to zero), this is due to the absence of the flare maneuver or at the very least a late flare maneuver. For the (4 deg) approaches also a large spread can be observed (see Figure 10c). This spread is present in the beginning and end of the training as well as in both the evaluation phases. The averages are 8.5 m (training) and 8.6 m (evaluation). Hence, the average flare initiation height does not show a change for the steeper approaches.

The haptics group shows, for the (3 deg) glideslope angle, from the beginning to the end of the training a higher consistency and less spread (see Figure 10b). The outliers also decrease. The average values are 5.8 m (training) and 6.1 m (evaluation). Hence there is a very slight increase after transfer. Both values are very close to the height where the High Roundout mode disappeared (5.7 m). For the (4 deg) approaches the spread decreases on day 1 but tends to increase again towards the end of the training. After the transfer the spread keeps increasing. There are no outliers present in the beginning but are consistently present in day 2. The measured averages are 7.6 m (training) and 8.4 m, denoting a somewhat larger increase further from the desired height (6.4 m).

A mixed-design ANOVA was performed to analyze the data. For the 3 deg case, no significant interaction effect was present ($F(2) = 1.2\ p \geq 0.05$, sphericity assumed). There was also no significant difference between the groups ($F(1, 14) = 0.824\ p \geq 0.05$). There was, however, a significant difference in phase ($F(2, 28) = 4.392\ p < 0.05$, sphericity assumed). Further investigation by means of paired samples t-tests for the phases (T1,T2,E1) resulted in no significant values. The ANOVA for the 4 deg approaches revealed no significant result for the phase ($F(2, 28) =$



(a) Baseline Group (3 deg) **(b) Haptics Group (3 deg)**



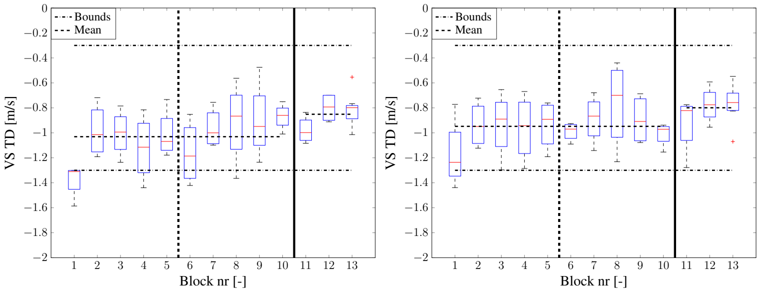
(c) Baseline Group (4 deg) **(d) Haptics Group (4 deg)**

Figure 10. Flare initiation height per block for different glideslope angles. The dashed line shows the separation between day 1 and day 2, the solid line denotes the end of the training phase.

$0.405\ p \geq 0.05$, sphericity assumed), for the interaction ($F(2) = 0.125\ p \geq 0.05$, sphericity assumed) or for the difference between groups ($F(1, 14) < 0.001\ p \geq 0.05$).

IV.C.2. Touchdown Vertical Speed

The boxplots in Figure 11 show the touchdown vertical speeds and are obtained by averaging data over subjects and gathered per block. The limits used to identify desired touchdown rates (-0.3 m/s and -1.3 m/s) are also presented in this Figure. The first block of the baseline group shows very high touchdown rates outside of the bounds. The spread is similar for the beginning and the end of the training. The values become more centered with respect to the limits towards the end of the experiment. The evaluation phase shows reduced spread and all values (including outliers) are within the set bounds. The average values for the baseline group are -1.03 m/s (training) and -0.85 m/s (evaluation). Similar trends are visible for the haptics group, however, the there are no values (except for the first block) outside of the bounds. The averages are equivalent: -0.95 m/s (training) and -0.80 m/s (evaluation).



(a) Baseline Group **(b) Haptics Group**

Figure 11. Touchdown rates for the baseline and the haptics groups. The dashed line highlights the separation of day 1 and day 2. The solid line denotes the end of the training phase. The dash-dot line denotes the bounds taken for the touchdown rate (-0.3 m/s and -1.3 m/s).

A mixed-design ANOVA was performed for this data. No significant effects were found for interaction between group and experiment phase ($F(1.22) = 0.813\ p \geq 0.05$, Greenhouse-Geisser) and for the between-subjects effect ($F(1,14) = 0.034\ p \geq 0.05$). A significant difference was found, however, for the phase ($F(1.22, 17.12) = 5.941\ p < 0.05$, Greenhouse-Geisser). This means that both the baseline and haptics groups show the same trend throughout the experiment (i.e., the values become more centered with respect to the desired bounds). Further investigation by means of paired samples t-tests in phase (T1,T2,E1) for both groups resulted in no significant values.

IV.C.3. Touchdown Location – Lateral

Figure 12 shows the distribution of landing locations in the lateral direction measured from the centerline. For every distance (i.e., between 0 m - 1 m, between 1 m - 2 m, ...) the number of touchdowns is given as a percentage. A differentiation is made between the different phases in order to have an overview of the evolution throughout the experiment. Note that in this figure no distinction is made between different runway widths or glideslope angles. The first training phase of the baseline group shows the highest percentage of landings (19%) between 1 m and 2 m to the left of the centerline. The largest offset measured is 10 m to the left. T2 has the highest percentage of landings (30%) between 0 m and 1 m to the left of the centerline. The maximum offset was too the left (6 m). During both evaluation phases of this group it can be seen that the spread is reduced compared with the training. For the first part of the evaluation phase (Eval. 1, see Figure 5), most landings (33%) occurred in a range of 0 m and 1 m to the right of the runway centerline, the maximum offset is determined to be 5 m to the left. For the second evaluation phase (Eval. 2, i.e., containing the extreme condition) most of the landings were in between 0 m and 1 m to the left of the centerline. Here the maximum offset is 6 m to the left. The haptics group also shows a decrease in spread throughout the experiment. The first training phase (T1) has a maximum measured lateral distance of 12 m to the left. The maximum occurrences (19%) were in between 1 m and 2 m left of the centerline. T2 has a maximum occurrence of landings (19%) both in between 0 m and 1 m, and 1 m and 2 m to the left. The largest offset was found to be 6 m. For the first evaluation phase there is a slight tendency of landing toward the left, the maximum measured offset was 8 m to the left while most of the landings (27%) occurred in between 0 m and 1 m to the left of the runway center. The last (extreme) evaluation phase shows a maximal offset to the left of 5 m and the most landings were performed between 0 m and 1 m to the left of the centerline.

A mixed-design ANOVA showed no significant results for the interaction effect ($F(1.04) = 0.132,\ p \geq 0.05$, Greenhouse-Geisser), as well as for the within-subject variable ($F(1.04, 14.56) = 2.364,\ p \geq 0.05$, Greenhouse-Geisser). There was a significant result for the difference between the groups ($F(1,14) = 11.929,\ p < 0.05$), which can be explained by the fact that in general the haptics group displayed more asymmetry to the left. This could be due to the position of the pilots in the cockpit. The right hand seat was used, so when the aircraft is on the runway, the centerline should be to the left of the pilot (i.e., not in front of the pilot).

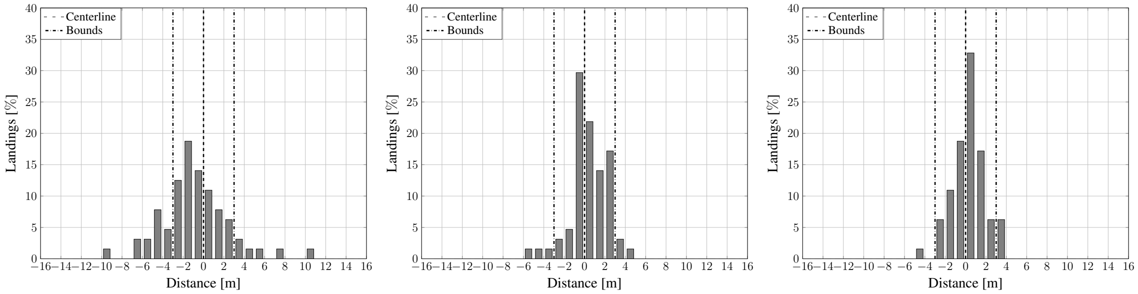
IV.C.4. Touchdown Location – Longitudinal

Figure 13 gives the touchdown distance on the runway, measured from the aiming point (see Figure 7) for both groups per block. The groups both show a decrease in spread throughout the experiment. The haptics group (averages of 171 m (training) and 178 m (evaluation)) shows less outliers than the baseline group (averages 166 m (training) and 154 m (evaluation)).

The mixed ANOVA performed for this data showed no significant results for the phase ($F(11.39, 19.34) = 0.422\ p \geq 0.05$, Greenhouse-Geisser). The interaction effect, however, was significant, highlighting that the change of distance on the runway over phases is not similar for both groups ($F(1.39) = 6.923\ p < 0.05$, Greenhouse-Geisser). Figure 13 shows that the mean values decrease throughout the experiment for the baseline group while for the haptics group the mean values increase. A significant difference between groups was also found ($F(1,14) = 5.783\ p < 0.05$). As for the lateral touchdown location results, there is wide variety of locations possible that are deemed to be desired. This variability can lead to differences between groups. Figure 13b shows that the differences between groups, in terms of desired performance (note the bounds), is minimial.

IV.D. Successful Landings

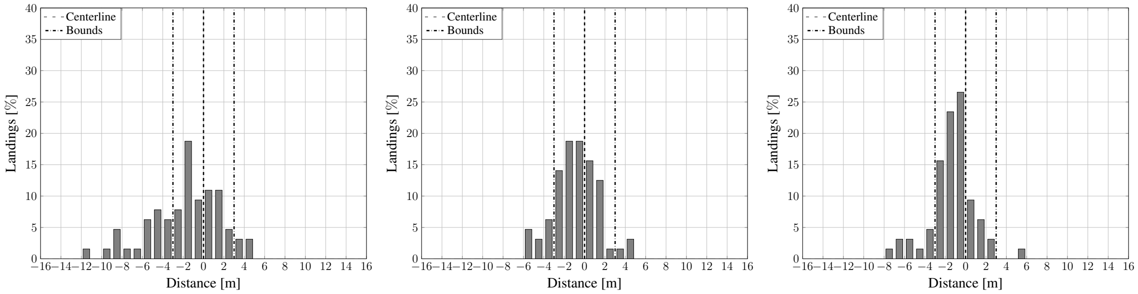
Figure 14 shows the percentage of successful landings (i.e., touchdown location and touchdown rate within the respective desired bounds). For the baseline group the performance is somewhat constant throughout the whole training phase (except block 1 which shows a lower success rate). In the first evaluation phase the number of successful landings remains approximately constant when compared with the last phase of the training. The averages are 45%



(a) Baseline T1

(b) Baseline T2

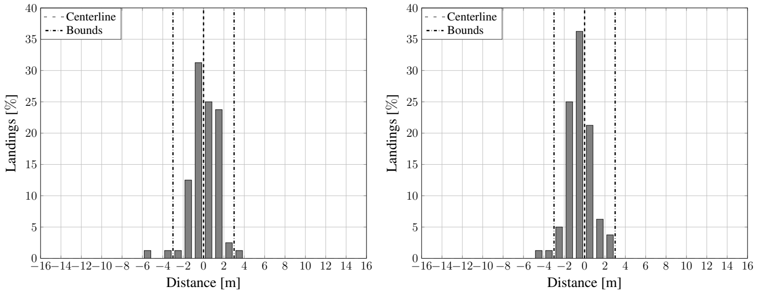
(c) Baseline E1



(d) Haptics T1

(e) Haptics T2

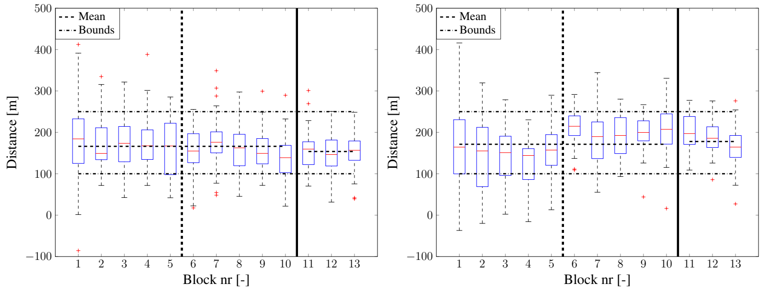
(f) Haptics E1



(g) Baseline E2

(h) Haptics E2

Figure 12. Dispersion of lateral touchdown location. Between bar separation is set on one meter. Offsets are measured from the runway centerline. The limits of the desired zone are given by the dash-dotted lines

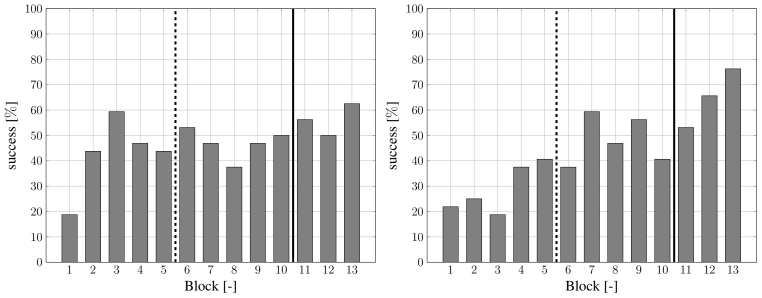


(a) Baseline Group

(b) Haptics Group

Figure 13. Touchdown distance on the runway. The thick dashed line highlights the separation of day 1 and day 2. The solid line denotes the end of the training phase. The thinner dashed line gives the mean. The bounds marking the desired location are 100 m and 250 m.

(training) and 56% (evaluation). The haptics group shows a clear learning effect when the first phase of training is compared with the end of training. The increase in performance proceeds in the first and even the second evaluation phase. In these phases the averages are 38% (training) and 65 % (evaluation).



(a) Baseline Group **(b) Haptics Group**

Figure 14. Percentage of successful landings. The dashed line highlights the separation of day 1 and day 2. The solid line denotes the end of the training phase.

Again a mixed-design ANOVA was performed, revealing a statistical significant difference for the phase ($F(2, 28) = 8.945$ $p < 0.05$, sphericity assumed). Hence, an overall significant increase in success rate is present. Further investigation (paired t-test) revealed no significance between the phases (T1,T2,E1). The lowest p value found ($p = 0.063$) was attributed to the comparison of the beginning of the training and the end of the training of the haptics group as can be expected by looking at Figure 14b. No significance was found for the interaction ($F(2) = 0.497$ $p \geq 0.05$, sphericity assumed) or for the between-group difference ($F(1, 14) = 0.003$ $p \geq 0.05$).

V. Discussion

The goal of this research was to design and evaluate a haptic aid to provide support for training of the manual landing flare. The haptic system used for this purpose provides three modes to counter common mistakes. An *ab initio* training experiment with 16 participants was performed to evaluate this haptic feedback.

V.A. Flare Trajectory Training

During the training phase, the participants in the haptics group were asked to state the perceived cues. It was noted that a clear difference in correct feedback recognition exists when comparing the first and the second day. The second day, in general, subjects had already developed a notion of flaring an aircraft and hence could spend more time and attention on achieving the correct flare trajectory and the correct motor action. Therefore, the feedback was also more correctly recognized when initially the final approach and flare approximated desired trajectories. Several participants also stated to have felt an active cue to the left or right (sometimes combined with pitch up or down e.g., a pull to the left). This can be explained by the fact that when people are correcting for a lateral offset (i.e., rolling to the left or right) at the same time they receive a LR or BA cue, the perception of lateral guidance is created. When novices learn to flare without prior flying experience, flying a stable approach can already pose a challenge. When the initial landing trajectory has too big of an offset with the desired path, the input necessary to correct for this exceeds normal training behavior as would be observed in real flight training. Additionally, this makes it difficult to provide needed (automated) haptic feedback.

When comparing the number of late roundouts between groups, one cannot detect a clear difference. The haptics group does not show better training behavior although in general this mode was activated less (22% - training, 18% - evaluation) compared with the baseline group (30% - training, 27% - evaluation). This can also clearly be seen when looking at the flare initiation heights of the baseline group, which shows more peaks in the direction of lower heights. For ballooning flares, interesting behavior can be observed. When looking at the count of BA mode activation, one sees very similar behavior between groups on day 1. This matches the earlier stated fact that feedback is noticed less on the first day. Day 2 shows a clear difference, the baseline group displays training behavior while this is not present for the haptics group. Participants seem to keep making mistakes leading to the activation of the BA cue although they perceive the feedback correctly. Firstly, one can hypothesize that the cues do not have enough authority and are being ignored. However, if this were true, it would result in similar behavior as the baseline on day 2. A second hypothesis is that subjects do not adopt feedback avoidance behavior but actually develop a strategy based on feeling the pulses. Subjects stated after the experiment that their main goal was to achieve the best discrete performance (i.e., touchdown performance) as possible. This is due to the fact that these parameters are given as feedback to the trainees after each landing. Hence, participants can link desired touchdown performance to a cue, resulting in a high consistency. As said before, the first evaluation phase shows an increase in the BA mode activation for the haptics group. When pilots use a strategy based on feeling the cues, they try to use the same strategy when the feedback is disabled.

Hypothesis H1 states that due to the haptic feedback, a faster reduction in occurrence of ballooning flares and late roundouts would be visible. The experiment showed that this is not the case (even the opposite occurred for ballooning flares). This is in contrast with literature ([22,29,30]), due to the lack of a feedback avoidance strategy by the participants.

The higher number of BA-LR activations for the haptics group, when compared to the baseline, can be explained by the effect of the repeated pulses. A pulse in the pitch up direction (LR) can induce a firm pitch up reaction leading to a balloon. The inverse is also true, a pitch down cue (BA) can lead to an activation of the LR mode. So, when too aggressive responses on haptic signals occur, other modes are activated. The increase on day 2 is in concurrence with the fact that the feedback in general is recognized better in the later stages of the training, hence more linked errors occur. The decrease in the evaluation phase is a direct result of the haptics being disabled in this phase.

V.B. Discrete Performance Training

When looking at discrete performance, more specifically, touchdown location performance, differences between the groups are subtle. The haptic feedback provided does not directly influence the touchdown location. The haptics group shows a significant difference, with respect to the baseline group, in skewness to the left of the centerline. This means that they have an increased effect of their position in the cockpit. When seating in the right hand seat the centerline should be to the left of the persons position when landing the aircraft. However, a tendency is observed to position the aircraft on the runway with the centerline right in front of the field of view of the participant.

The number of successful landings remains fairly constant for the baseline group, showing that this group actually has good performance from the start of the experiment. There is a training effect visible when looking at the first three blocks. The first block shows the least amount of successful landings which can be explained by looking at the touchdown rates of this block. For the augmented group the performance in terms of successful landings increases while the number of haptic activations does not decrease (it even increases for BA) throughout the experiment. This disproves the statement that the improvement in touchdown location should be a consequence of better flare trajectories. However, it is in concurrence with the theory that a dependency on the cues related to flare strategy occurs. Participants link desired touchdown performance to haptic cues and therefore learn to cope with these mistakes in the trajectory. This can also be seen in the continued performance improvement in the evaluation phase.

The discrete performance also encompasses the flare initiation height. It was hypothesized (**Hypothesis H2**) that when using the passive part of the haptic feedback, learning would be improved and perhaps accelerated. The general trend in the baseline training is that the trainees initiate the flare too high. The haptics group shows a very high consistency in the training phase and contains less outliers compared with the baseline group. The average flare height over the training phase is lower, approaching a more correct flare start height. Hence, the haptic feedback was clearly used as tool by the participants from the beginning to the end of the training phase and provided the trainees with an aid to determine the correct timing. Therefore, Hypothesis 2 is partly confirmed.

V.C. Transfer of Training

From the data it can be determined that no significant training dependency is created on neither of the ballooning and late roundout cues. It is hypothesized, however, that the subjects use the cues to maintain consistency, by linking the haptic feedback to desired touchdown metrics. This is supported by the statistical tests performed. For the touchdown metrics, the performance was retained or even improved in the evaluation phase, no worsening after transfer was observed. Regarding the flare initiation height, no significant difference was found between the evaluation and the training phases for the haptics group. This suggests that no meaningful dependency is created on this cue. Also, no significant difference was found between the groups, meaning that the haptics group performed at least as good as the baseline group after transfer for this metric.

In general, no consistent worsening of the metrics can be observed in the last evaluation block (i.e., the extreme condition (S5)), suggesting generalizability of the skills. The number of successful landings even shows a peak for both groups in this condition. Also the lateral offset from the centerline shows the least spread in this condition. The only small worsening effect observed is in the number of late roundout activations. This can be explained by the steep approach angle and small runway width. This creates the sense of being too high, thereby increasing the chance of flaring too late.

Hypothesis 3 stated that no dependency on the haptic feedback would be created and generalizability of the skills can be assumed. There is in general no significant difference found between the last training phase (T2) and the first evaluation phase (E1). However, the data show evidence of dependency creation to maintain consistency. Hence, the off-target nature of the feedback was not used properly by the subjects. There is no sign of worsening of the performance metrics could be found in the second evaluation phase. Therefore, Hypothesis 3 is partially confirmed.

V.D. General Flare Training and Experiment Remarks

The participants of the experiment mainly focused on obtaining desired touchdown performance. This can be explained by the fact that touchdown performance feedback was given to the pilots after each run, forcing their focus on this. Therefore, it can be beneficial to train pilots in different stages. This would create the ability for novices to focus on multiple, separated, goals. This idea is supported from the notion that although worsening of trajectory mistakes is present, discrete performance measures can still be desired. The first stage of such training could be the approach, flying consistent paths towards the aiming point. The second stage in the training could then focus on achieving the correct flare initiation point. This can be supported by passive haptic feedback and/or visual augmentation.[9] The next stage would be to focus on the correct flare trajectory by enforcing the cue avoidance strategy.

Furthermore, with the lessons learned from the current study, the haptic aid itself can also be improved. For example, an important aspect is the fact that this haptic aid system was not adaptable. Hence, every operator received exactly the same feedback. Differences in the way pilots manipulate the controller exist but are not incorporated in the feedback. Therefore, fixed magnitude pulses can result in different perception of this cue. For this experiment the assumed conditions included. 1) a stable final approach, 2) a feedback avoidance strategy, and 3) use of the side-stick in such a way to perceive the feedback correctly. It was found that these conditions were not always met and as such surpassing the purpose of the haptic augmentation, leading to disuse of the haptic aid.[45,46] This, in turn, led to the loss of potential training benefit.

In addition, the designed haptic aid uses a virtual fixtures implementation and haptic signaling (pulses) to provide "live" haptic feedback while trainees are performing the flare maneuver. A second potentially valuable use of haptics for training is to demonstrate the control forces needed for good flare execution, equivalent to how instructors show the to be performed actions while the student follows by passively holding the (second) control wheel.[20]

VI. Conclusion

A haptic training aid for supporting *ab initio* manual landing flare training was developed, with the goal of providing off-target feedback to prevent three typical mistakes in executing the flare. To verify the effectiveness of the developed haptic aid, a transfer-of-training experiment with two groups (baseline and haptics) was performed with 16 novice participants, who were trained to perform the flare maneuver with a small jet aircraft. Overall, the designed haptic feedback was found to result in only minor initial training benefits. Due to the short duration of the flare maneuver and the difficulty of the task, the haptic feedback did not always provide added insight to trainees, and was in some cases found to induce additional errors due to too strong responses to the successive haptic feedback activations. The novice participants did not seem to develop a feedback avoidance strategy, but they tended to use the haptic cues to verify their strategy for obtaining desired touchdown performance. However, the designed High Roundout (HR) mode, with increased the stiffness of the side-stick for preventing pitch-up control inputs when still above the desired flare altitude, was found to help in training the correct flare height. The data from the haptics group show less spread in the flare initiation height when compared to the baseline group. After transfer to a scenario without the haptic aid, no dependency on the availability of this feedback was detected. Thus, presenting changing task restrictions through haptic feedback shows clear potential as a training aid for maneuvers with critical timing, such as the landing flare.

References

[1] Haslbeck, A., Schubert, E., Onnasch, L., Hüttig, G., and Bubb, H., "Manual flying skills under the influence of performance shaping factors," *WORK*, Vol. 41, 2012, pp. 178–183.

[2] Benbassat, D. and Abramson, C. I., "Landing Flare Accident Reports and Pilot Perception Analysis," *The International Journal of Aviation Psychology*, Vol. 12, No. 2, 2002, pp. 137–152.

[3] Boeing Commercial Airplanes, "Statistical Summary of Commercial Jet Airplane Accidents," Tech. rep., 2016.

[4] Shea, C. H., Wulf, G., and Mcnevin, N. H., "Increasing the distance of an external focus of attention enhances learning," *Psychological Research*, , No. February, 2003, pp. 22–29.

[5] Lintern, G., Roscoe, S. N., and Segal D, L., "Transfer of Landing Skills in Beginning Flight Training," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, Vol. 32, No. 3, 1990, pp. 319–327.

[6] Le Ngoc, L., Borst, C., Mulder, M., and van Paassen, M. M., "The Effect of Synthetic Vision Enhancements on Landing Flare Performance," *AIAA Guidance, Navigation and Control Conference*, No. August, 2010.

[7] Jacobson, D., "Where to Flare?" *The 1987 Australian Aviation Symposium*, , No. November, 1987, pp. 125–128.

[8] Robson, D., "The Gentle Touch - Landing an Aircraft Safely, Consistently and Well," *Australian Aviation Symposium:'Innovate or Enervate' Canberra, November 18-20*, 1987, pp. 129–131.

[9] Ravesteijn, C., Borst, C., Pool, D. M., van Paassen, M. M., and Mulder, M., *MSc. Thesis*.

[10] Jennett, S., *Churchill Livingstone's Dictionary of Sport and Exercise Science and Medicine*, Elsevier Ltd, 2008.

[11] Fitts, P. M., "Perceptual-Motor Skill Learning," *Categories of Human Learning*, Academic Press Inc., 1964, pp. 244–283.

[12] Rasmussen, J., "Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models," *IEEE Transactions on Systems, Man , and Cybernetics*, 1983, pp. 257–266.

[13] Kantak, S. S. and Winstein, C. J., "Learning performance distinction and memory processes for motor skills : A focused review and perspective," *Behavioural Brain Research*, Vol. 228, No. 1, 2012, pp. 219–231.

[14] Srimathveeravalli, G., Gourishankar, V., and Kesavadas, T., "Comparative Study : Virtual Fixtures and Shared Control for Rehabilitation of Fine Motor Skills," *Proc. World Haptics, 2007*, 2007, pp. 304–309.

[15] Schmidt, H., Krüger, J., and Hesse, S., "HapticWalker - haptic foot device for gait rehabilitation," *Human Haptic Perception: Basics and Applications*, 2008, pp. 501–511.

[16] Zhong, P. and Stone, R. T., "Automated kinesthetic trainer enhances kinesthetic memory development," *International Journal of Industrial Ergonomics*, Vol. 43, No. 3, 2013, pp. 238–245.

[17] Rosenberg, L. B., "Virtual Fixtures : Perceptual Tools for Telerobotic Manipulation," *Proceedings of IEEE Virtual Reality Annual International Symposium*, 1993, pp. 76–82.

[18] Abbink, D. A. and Mulder, M., "Exploring the dimensions of haptic feedback support in manual control," *Journal of Computing and Information Science in Engineering*, Vol. 9, 2009, pp. 1–9.

[19] Feygin, D., Keehner, M., and Tendick, F., "Haptic Guidance : Experimental Evaluation of a Haptic Training Method for a Perceptual Motor Skill," *IEEE Proceedings of the 10th Symposium On Haptic Interfaces For Virtual Environment & Teleoperator Systems*, 2002.

[20] D'Intino, G., Olivari, M., Geluardi, S., Venrooij, J., Pollini, L., and Bülthoff, H. H., "Experimental Evaluation of Haptic Support Systems for Learning a 2-DoF Tracking Task," *AIAA SciTech Forum*, No. January, 2017, pp. 1–10.

[21] Honing, V., Gibo, T. L., Kuiper, R. J., and Abbink, D. A., "Training with haptic shared control to learn a slow dynamic system," *IEEE International Conference on Systems, Man and Cybernetics*, 2014, pp. 3126–3131.

[22] de Groot, S., de Winter, J. C. F., Manuel, J., García, L., Mulder, M., and Wieringa, P. A., "The Effect of Concurrent Bandwidth Feedback on Learning the Lane-Keeping Task in a Driving Simulator," *Human Factors and Ergonomics Society*, Vol. 53, No. 1, 2011, pp. 50–62.

[23] Lam, T. M., Boschloo, H. W., Mulder, M., and van Paassen, M. M., "Artificial Force Field for Haptic Feedback in UAV Teleoperation," *IEEE Transactions on Systems, Man , and Cybernetics- Part A: Systems and Humans*, Vol. 39, 2009, pp. 1316–1330.

[24] Goodrich, K., Schutte, P., and Williams, R., "Piloted Evaluation of the H-Mode, a Variable Autonomy Control System, in Motion-Based Simulation," *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, 2008, pp. 1–15.

[25] Matheny, N. W., "Flight Investigation of Approach and Flare From Simulated Breakout Altitude of a Subsonic Jet Transport and Comparison With Analytical Models," 1974.

[26] European Aviation Safety Agency, "Acceptable Means of Compliance and Guidance Material to Part-FCL 1," 2011, pp. 1–562.

[27] U.S. Department of Transportation Federal Aviation Administration, "Techniques of Flight Instruction," *Aviation Instructor's Handbook*, 2008, pp. 8–12.

[28] Federal Aviation Administration, "Chapter 8 - Approaches and Landings," *Airplane Flying Handbook*, 2004, pp. 8–1 – 8–34.

[29] Swinnen, S. P., "Information Feedback for Motor Skill Learning: A Review," *Advances in Motor Learning and Control*, 1996, pp. 37–65.

[30] Schmidt, R. A. and Lee, T. D., *Motor Control and Learning*, Human Kinetics, 5th ed., 1999.

[31] Lintern, G., "Transfer of Landing Skill After Training with Supplementary Visual Cues," *Human Factors*, Vol. 22, No. 1, 1980, pp. 81–88.

[32] O'Malley, M. K., Gupta, A., Gen, M., and Li, Y., "Shared Control in Haptic Systems for Performance Enhancement and Training," *Journal of Dynamic Systems, Measurement, and Control*, Vol. 128, No. March, 2006, pp. 75–85.

[33] Mulder, M., Pleijsant, J. M., van der Vaart, H., and van Wieringen, P., "The Effects of Pictorial Detail on the timing of the Landing Flare: Results of a Visual Simulation Experiment," *The International Journal of Aviation Psychology*, Vol. 10, No. 3, 2000, pp. 291–315.

[34] Stroosma, O., van Paassen, M. M., and Mulder, M., "Using the SIMONA Research Simulator for Human-machine Interaction Research," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, 2003, pp. 1–8.

[35] Entzinger, J. O. and Suzuki, S., "Inside the pilot's mind : Visual information use in manual aircraft landings," *28th international congress of the aeronautical sciences*, No. January, 2012, pp. 1–10.

[36] Ridgway, G. R. and Jump, M., "Arresting a Descent: What Cues do Pilots Use to Initiate a Flare Maneuver?" *AIAA Guidance, Navigation and Control Conference*, No. August, 2011, pp. 1–13.

[37] ICAO, *Aerodrome Standards: Aerodrome Design and Operations*, 1999.

[38] Pool, D. M., Harder, G. A., and van Paassen, M. M., "Effects of Simulator Motion Feedback on Training of Skill-Based Control Behavior," *Journal of Guidance, Control, and Dynamics*, Vol. 39, No. 4, 2016, pp. 889–901.

[39] Mulder, M. and Mulder, J. A., "Cybernetic Analysis of Perspective Flight-Path Display Dimensions," *Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 398-411, 2005.

[40] Arents, R. R. D., Groeneweg, J., Borst, C., van Paassen, M. M., and Mulder, M., "Predictive Landing Guidance in Synthetic Vision Displays," *The Open Aerospace Engineering Journal*, , No. 4, 2011, pp. 11–25.

[41] Jump, M. and Padfield, G. D., "Investigation of the Flare Maneuver Using Optical Tau," *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 5, 2006, pp. 1189–1200.

[42] van Es, G., van der Geest, P., Cheng, A., Hackler, L., and Dillard, A., "A Study of Normal Operational Landing Performance on Subsonic , Civil , Narrow-Body Jet Aircraft During Instrument Landing System Approaches," Tech. Rep. March, NLR, 2007.

[43] Beukers, J. T., Stroosma, O., Pool, D. M., Mulder, M., and van Paassen, M. M., "Investigation into Pilot Perception and Control During Decrab Maneuvers in Simulated Flight," *Journal of Guidance, Control, and Dynamics*, Vol. 33, No. 4, 2010.

[44] Field, E. J., Pinney, T. R., van Paassen, M. M., and Stroosma, O., "Effects of Implementation Variations on the Results of Piloted Simulator Handling Qualities Evaluations," *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, No. August, 2004, pp. 1–16.

[45] Abbink, D. A., Mulder, M., and Boer, E., "Haptic shared control : smoothly shifting control authority?" *Cognition Technology and Work*, 2012, pp. 19–28.

[46] Parasuraman, R. and Riley, V., "Humans and Automation: Use, Misuse, Disuse, Abuse," *Human Factors*, Vol. 39, No. 2, 1997, pp. 230–253.

Appendix A Flare Time-to-Contact

This appendix explains how the Jacobson flare is used to determine the difference in Time To Contact limit value and flare height for a 3° and 4° glideslope.[7] Jacobson defined a geometrical method to help pilots determine the correct altitude to start the flare. The method comprises of flying towards an aiming line on the runway and starting the flare when passing the so-called cut-off line (which is in front of the aiming line). Both lines are geometrically linked, equation 4 gives the distance between the respective lines (Δf). For the aircraft depended values, a Cessna Citation I is used. The height of the pilot's eye on flare initiation is given by $h_{eye_{flare}}$ and is equal to the flare altitude of the aircraft c.g. for the respective glideslope angle, added with 1.07 m. The flight path angle either 3° or 4° and is denoted by γ. κ_a is the cockpit cut-off angle ($\kappa = 13°$) corrected for the pitch angle θ.

$$\Delta f = h_{eye_{flare}} \left(\frac{1}{\tan(\gamma)} - \frac{1}{\tan(\kappa_a)} \right) \tag{4}$$

Previous landing experiments done using the same model revealed a difference of 9.7m between the cut-off line for a 3° and 4° glideslope.[9] Using an approach speed (V_{app}) of 98 kts (≈ 50.42 m/s), the difference in Time To Contact is approximately 0.2s. Using a vertical speed of 3.49 m/s (4°) the difference in flare height amounts 0.7 m.

Appendix B Flare Initiation Detection

The flare initiation point was determined using the longitudinal stick deflection signal. There were 2 detection iterations. The stick deflection signal was filtered with a moving average filter (MAV) using both the short period time period ($T = 2.98s$) and the phugoid eigenmotion time period ($T = 28.2s$) as window size.[43]

For the first iteration, two windows were defined ($T = 2.98s$) which moved over the short period filtered signal creating linear fits in each adjacent window. The point where the difference in slopes, which are corrected for the goodness of fit (i.e., to eliminate the detection of strong fluctuations), of the fits is maximized. To narrow the search, the windows started after 15 seconds, as it is hypothesized that before this time nobody initiates the flare.

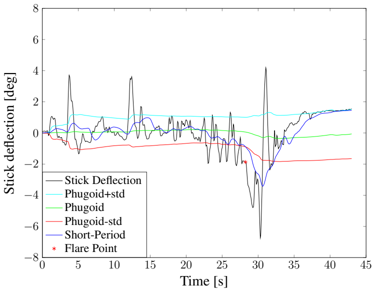


Figure 15. Depiction of the second method used to determine the flare initiation point.

Every flare initiation detection was checked manually, when corrections were deemed necessary, a second iteration was performed. For this, the standard deviation of the original signal was calculated using the interval of the phugoid MAV and was added and subtracted to the phugoid filtered signal. The signals resulting from this create a band. The control strategy is assumed to change if the short-period filtered signal leaves this band.[40] Figure 15 depicts this second iteration. The advantage of the method of the first iteration is that it is not subjected to the small delay present in the second method.