Autorotation Transfer of Training: Effects of Helicopter Dynamics Variation

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I. Introduction

Autorotation is a flight condition where the rotation of the rotor is sustained by the airflow moving up through the rotor, rather than by means of engine torque applied to the shaft. Helicopter pilots use autorotation following partial or total engine power failure to reach the nearest suitable landing site. The energy stored in the rotor is preserved at the expense of the helicopter's potential energy, i.e., the altitude. Therefore, a helicopter can sustain autorotation only by means of descending flight.

Autorotation is considered to be a key critical training scenario for helicopter pilots [1–3]. Indeed, the development of a standardized training program for autorotation and emergency aircraft handling, as well as the improvement of simulator training for basic (e.g., hover) and advanced (e.g., autorotation) maneuvers, are essential to enhance rotorcraft safety, as suggested by several accident analyses [4–7].

Especially for a critical hands-on maneuver such as autorotation, pilots need to adjust their control strategy according to the helicopter dynamics they control [8–10]. Helicopters with different handling characteristics may require very different skills from pilots to accomplish the task. However, only a few studies have explicitly investigated the effects of rotorcraft model fidelity and dynamics variations on pilot behaviour and (transfer of) training, e.g., [11–14].

Experimental evidence suggests that simulator training for the lateral sidestep hover maneuver [11] and for

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autorotation [14] can best start with training in the most resource demanding condition, corroborating perceptual learning theory [15]. Indeed, difficult dynamics require rapid responses to perceptual changes, forcing pilots to develop more robust and adaptable flying skills. This can enhance helicopter safety as pilots will be better prepared to face unexpected events that may occur during actual flight.

To confirm previous experimental findings [11, 14], this paper investigates whether the acquisition of flying skills for autorotation, and their transfer, are affected by the helicopter dynamics. Two dynamics with a very different control feel were tested, characterized by a different autorotative index [16]: 1) "hard", i.e., lower autorotative index, thus high pilot compensation required and 2) "easy", i.e., higher index, with low compensation required.

A quasi-Transfer-of-Training (qToT) experiment with experienced helicopter pilots is being conducted in TU Delft's SIMONA Research Simulator (SRS) (Fig. 2). They will be divided in two groups and trained to perform a straight-in autorotation maneuver (Fig. 1) controlling a seven degrees of freedom non-linear helicopter model with 6-DOF rigid-body dynamics plus rotorspeed. Each group will test the two sets of dynamics in a different training order: hard-easy-hard (HEH group) and easy-hard-easy (EHE group). Performance of the two groups in the three training phases will be compared based on four metrics at touchdown: horizontal speed, rate of descent, pitch angle and pitch rate. In line with aforementioned previous experimental evidence [11, 14] and perceptual learning theory [15], we hypothesized that both groups exhibit positive transfer of training from the hard to the easy dynamics, but not from the easy to the hard dynamics.

II. Methods

A. Task

Experimental tasks are usually defined according to the specifications of the mission-oriented design standard, the ADS-33E [17]. Although conceived for military rotorcraft, the ADS-33E are widely used to assess handling qualities characteristics of commercial rotorcraft as well, as there is no counterpart in the civil domain. However, the use of ADS-33E Mission Task Elements (MTEs) is not always relevant, especially in the design of training tasks. Furthermore, the ADS-33E does not have a specific Autorotation Maneuver MTE. Therefore, performance of pilot-in-the-loop autorotation maneuvers are usually evaluated based on subjective pilot feedback and comments and on objective measurements of landing survivability metrics [18].

For this experiment, a MTE was defined for the straight-in autorotation maneuver; the proposed test course is shown in Fig. 1. The simulation starts with the helicopter trimmed in straight level flight at 60 knots air speed, at an altitude of 1.000 ft. The symmetry plane of the helicopter is aligned with the center line of a runway, whose starting point is located 1.000 m ahead the helicopter initial position. The pilot has to keep constant speed and altitude until the power failure is triggered from the control room. As soon as the pilot recognizes the unannounced failure, he has to recover starting a steady descent in autorotation, maintaining 60 knots air speed and keeping the rotor RPM in the green arc of the tachometer. When close enough to the ground the pilot has to flare, to reduce both the rate of descent and the forward speed and finally level the skids with the ground, to avoid tail strike, and pull-up the collective to cushion the touchdown. The contact accelerations at touchdown were not modeled. Therefore, the simulation stopped automatically once the center of gravity of the helicopter reached two meters above the ground.

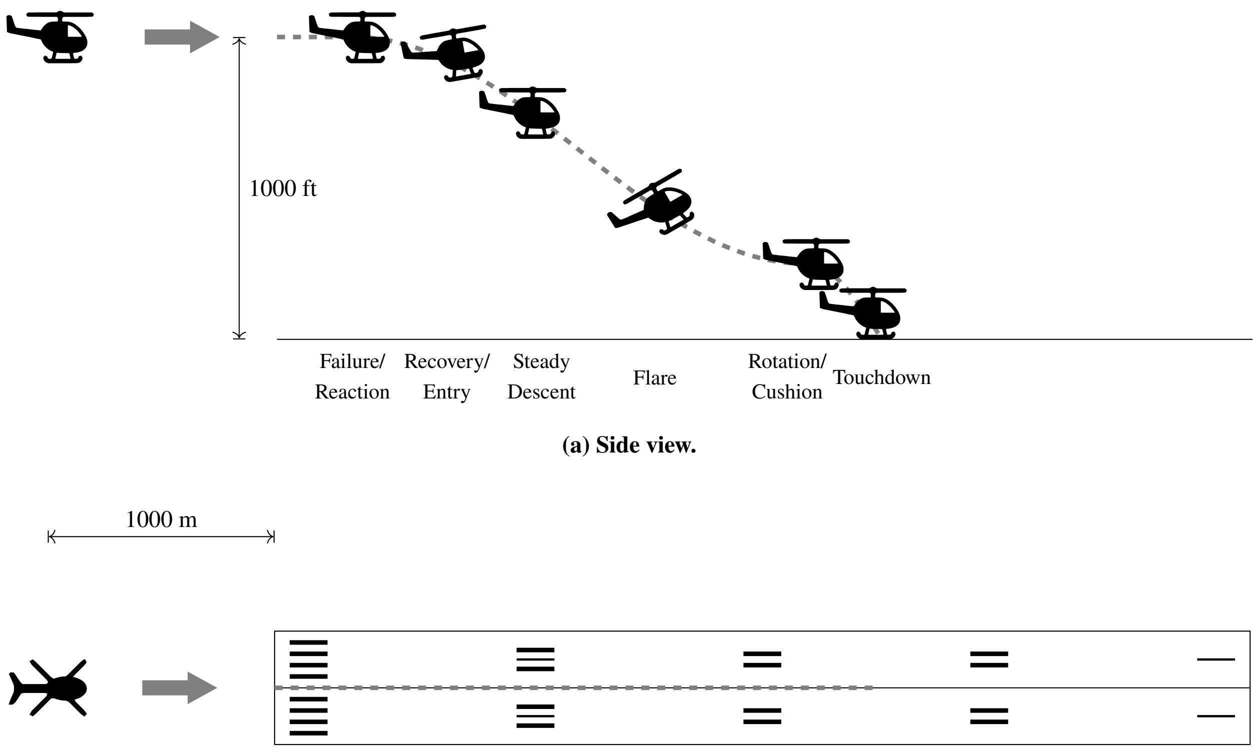


Fig. 1 Suggested course for straight-in autorotation maneuver.

Performance standards for the straight-in autorotation maneuver are adapted from Sunberg et al. [18, 19] and are listed in Tab. 1. The values of the horizontal speed and of the rate of descent at touchdown refer to the AH-1G helicopter [18], which has a similar skid landing gear as the baseline helicopter (Bo-105) considered in this paper. Therefore, these were not changed. Although characterized by a similar landing system, the AH-1G and the Bo-105 are different helicopters, with different performance and intended role. Indeed, the AH-1G is a two-blades rotor, single-engine attack helicopter, whereas the Bo-105 is a light, twin-engine, multi-purpose helicopter with a four-blades hingeless rotor. The maximum values of the pitch angle at touchdown, which are responsible of preventing tail strike, were slightly increased due to the different helicopter geometry. Desired performance translates into a successful landing, i.e., the helicopter's final state at ground contact is such that the aircraft and crew survivability are not threatened. Adequate performance translates into marginal landing conditions, that would likely result in damage to the aircraft, but be survivable to the occupants and the equipment. The values presented in Tab. 1 are defined according to landing survivability metrics that are based on specifications for military helicopters' structural design [20, 21] and on the accident analysis conducted by Crist and Symes [22].

Table 1 Performance – Straight-in Autorotation Maneuver (adapted from Sunberg et al. [18]).

Metric	Performance			
	Desired		Adequate	
	Minimum	Maximum	Minimum	Maximum
Roll angle at touchdown ϕ_{td} (deg)	−5	5	−10	10
Pitch angle at touchdown θ_{td} (deg)	−5	12	−5	18
Forward speed at touchdown $V_{x_{td}}$ (kn)	0	30	0	40
Lateral speed at touchdown $V_{y_{td}}$ (ft/s)	−3	3	−6	6
Rate of descent at touchdown $V_{z_{td}}$ (ft/min)	0	480	0	900
Roll rate at touchdown p_{td} (deg/s)	−8	8	−15	15
Pitch rate at touchdown q_{td} (deg/s)	−10	10	−20	20
Yaw rate at touchdown r_{td} (deg/s)	−8	8	−15	15

B. Helicopter Dynamics

Participants performed the straight-in autorotation task by controlling a seven degrees-of-freedom (6-DOF rigid-body dynamics plus rotorspeed DOF), non-linear and generic helicopter model with quasi-steady flapping dynamics [23]. This generic model can be used in combination with different parameters sets to approximate the dynamic response of any conventional helicopter configuration.

From the wide range of configurations studied by Scaramuzzino et al. [23], two were selected for a previous study [14], in which a four degrees-of-freedom (3-DOF longitudinal dynamics plus rotorspeed DOF) helicopter model was used. The "hard" dynamics is representative of the Bo-105 helicopter and was taken from Padfield [24]. The "easy" dynamics represents a variation of the Bo-105 helicopter with reduced weight in order to achieve a higher autorotative flare index (AI) [16]. The same configurations were considered in the current experiment to corroborate the results obtained by Scaramuzzino et al. [14] with a simpler model.

C. Experiment Structure

The experiment is structured as in Tab. 2 and consists of four phases:

1) Familiarization: this phase was intended to help the participants get acquainted with the simulation environment (helicopter model, cockpit ergonomy, control inceptors, etc.). For this reason, the simulator motion system was disabled and each participant performed the task with either the hard or the easy helicopter dynamics. These runs will not be used in the analysis.
2) Training: each participant performed the task with the same helicopter dynamics used during the Familiarization phase. Starting from this session, the simulator motion system was enabled.

3) Transfer: each participant performed the task with the other helicopter configuration.

4) Back-transfer: each participant performed the task with the initial hard/easy helicopter configuration.

In total, each participant was trained in the simulator for approximately 3 hours.

Table 2 Experiment phases.

Phase	HEH group	EHE group	Duration	Motion
Familiarization	Hard helicopter dynamics	Easy helicopter dynamics	3 autorotative landings	Off
Training	Hard helicopter dynamics	Easy helicopter dynamics	15 autorotative landings	On
Transfer	Easy helicopter dynamics	Hard helicopter dynamics	15 autorotative landings	On
Back-Transfer	Hard helicopter dynamics	Easy helicopter dynamics	15 autorotative landings	On

D. Dependent measures

To investigate the effect of the helicopter dynamics (independent variable) on autorotation performance and training, the dependent measures related to the MTE definition presented in Tab. 1 were considered.

E. Hypotheses

For this experiment only one main hypothesis was tested. Based on previous experimental evidence [11, 14] and on current in-flight training procedures, it is envisioned that pilots who start the training with the most challenging configuration (hard dynamics), are more likely to develop robust and flexible autorotation skills that can be easily adapted to different helicopter configurations and dynamics. Therefore, it is expected that flying skills are positively transferred from the hard to the easy dynamics, but not conversely. When positive transfer happens, we expect to see lower rates of descent after transition to a different dynamics, as a lower descent rate is a key indicator for a controlled and smooth touchdown [3]. Among all the dependent measures, the rate of descent is thus expected to cover a key role to corroborate our hypothesis.

F. Participants

At least ten experienced helicopter pilots with a different background (license type), with a mix of civil and military experience and with a different in-flight and simulator experience will take part in the experiment. Participants will be divided in two groups in such a way that they have, on average, a comparable number of flight hours and a similar distribution. Beside the number of flight hours, also pilots background will be considered during the separation of the pilots in the two groups.

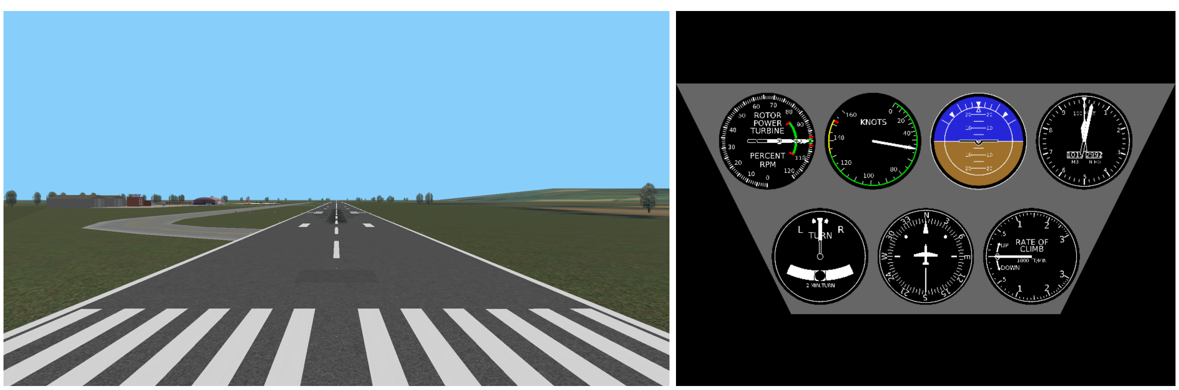
Participants will sign an informed consent prior to the experiment. The experiment has been approved by the Human Research Ethics Committee of Delft University of Technology under the approval letter number 1423.

G. Apparatus

The experiment was conducted in the SIMONA Research Simulator (SRS) (Fig. 2), which is a moving-base simulator at the Faculty of Aerospace Engineering of TU Delft [25]. The SRS is equipped with a 6 degrees-of-freedom hydraulic motion system, which was used in the experiment to provide motion cues.

Fig. 2 The SIMONA Research Simulator at Delft University of Technology.

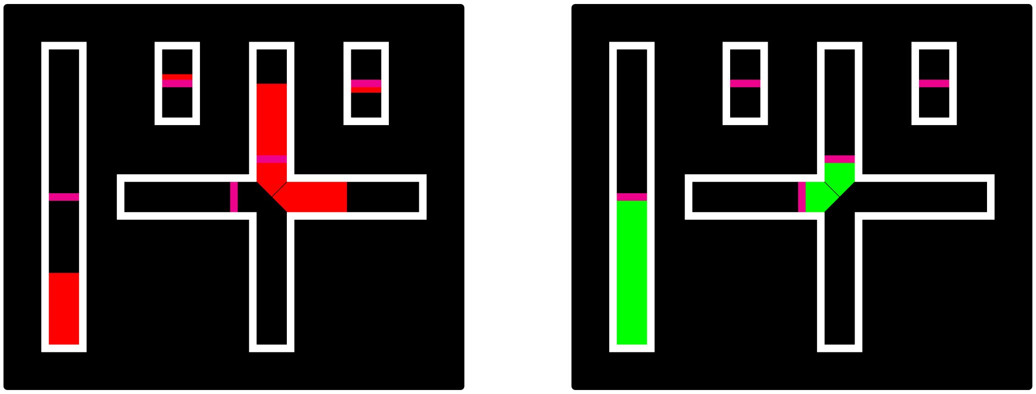
In terms of visual equipment, the SRS is fitted with a $180° \times 40°$ 3-projector Digital Light Processing (DLP®) collimated display. A representative out-of-the-window scenery was presented on this display (Fig. 3a). Furthermore, an instrument panel (Fig. 3b), consisting of a tachometer, airspeed indicator, artificial horizon, altimeter, yaw string, compass and vertical speed indicator, and a trim display (Fig. 4) were projected on two monitors inside the cockpit. Pilots use the trim display only before the start of each run in order to find the trim position of all the flight controls. This enables them to keep the initial equilibrium condition (straight level flight at 60 kn) and avoid a transient response to reestablish it.



(a) Out-of-the-window scenery. **(b) Instrument panel.**

Fig. 3 Out-of-the-window scenery and instrument panel used for the current experiment.

The right seat of the cockpit was equipped with a realistic helicopter control inceptor with programmable control loading system, whose parameters were set as reported in Tab. 3 after consultation with test pilots [26].



(a) Out of trim. (b) In trim.

Fig. 4 Trim display.

Table 3 Control loading settings.

Parameter	Longitudinal Cyclic	Lateral Cyclic	Collective
Periodic			
Forward friction level (N)	2.0	2.0	6.0
Positive forward stop (deg)	15.0	15.0	16.0
Negative forward stop (deg)	−15.0	−15.0	−16.0
Non periodic			
Linkage stiffness (N/deg)	50.0	50.0	50.0
Linkage damping (N s/deg)	0.01	0.01	0.01
Positive aft travel limit (deg)	14.8	14.8	15.8
Negative aft travel limit (deg)	−14.8	−14.8	−15.8
Aft friction (N)	2.0	2.0	6.0
Aft inverse damping (deg/N/s)	10.0	10.0	10.0
Second feel spring slope (N/deg)	3.0	3.0	0.0
Breakout level (N)	0.0	0.0	0.0

Rotor sound was played during the simulation to increase immersion. The sound was modulated based on the value of the rotor RPM, so that the participant could use sound cues as a source of information to control the rotor RPM, rather than by looking at the instrument panel. Moreover, a low-RPM acoustic warning was activated every time the rotorspeed dropped below 85%. The low-RPM warning was used as a backup cue for the rotor sound, so that the failure could be recognized without necessarily looking at the instruments. Engine sound was not included.

H. Motion Filter Tuning

The Classical Washout Algorithm (CWA) is used to map the vehicle motion on the simulator workspace [27]. The three high-pass filters related to the longitudinal dynamics (the pitch, surge and heave axes) were set according to the tuning conducted by Scaramuzzino et al. [14] on a four degrees-of-freedom (3-DOF longitudinal dynamics plus rotorspeed DOF) helicopter model. So these filters were selected to be of second order for the pitch and surge axes, and of third order for the heave axis. Although surge and heave axes are both translational degrees of freedom, a different order of the filter was selected for these two axes. Indeed, a second order high-pass filter along the surge axis allows to achieve sufficient washout through the use of tilt coordination. This was first observed by Reid and Nahon [28] and reiterated by Grant [29]. Therefore, the combination of the tilt coordination and the body to inertial transformation effectively adds one order of washout.

The high-pass filter parameters related to a rotational DOF in the lateral-directional dynamics (the roll and yaw axes) were set equal to those along the pitch axis. The high-pass filter parameters related to the sway axis were set equal to those along the surge axis.

The final motion filter settings for the 6 degrees-of-freedom are presented in Tab. 4.

Table 4 Motion cueing settings.

DOF	K (-)	ω_n (rad/s)	ζ (-)	ω_b (rad/s)	Order (-)
Longitudinal Dynamics					
Heave	0.5	3.5	0.7071	0.2	3
Surge	0.5	1.5	0.7071	0.0	2
Pitch	0.5	1.5	0.7071	0.0	2
Lateral-Directional Dynamics					
Yaw	0.5	1.5	0.7071	0.0	2
Sway	0.5	1.5	0.7071	0.0	2
Roll	0.5	1.5	0.7071	0.0	2

III. Preliminary Results

At least ten pilots will be included in this study. However, so far only 4 of them participated in the experiment, i.e., two pilots per group. The current size of the sample does not allow any statistical analyses, but it is still possible to look at individual data to understand if there is a recurrent trend among the participants.

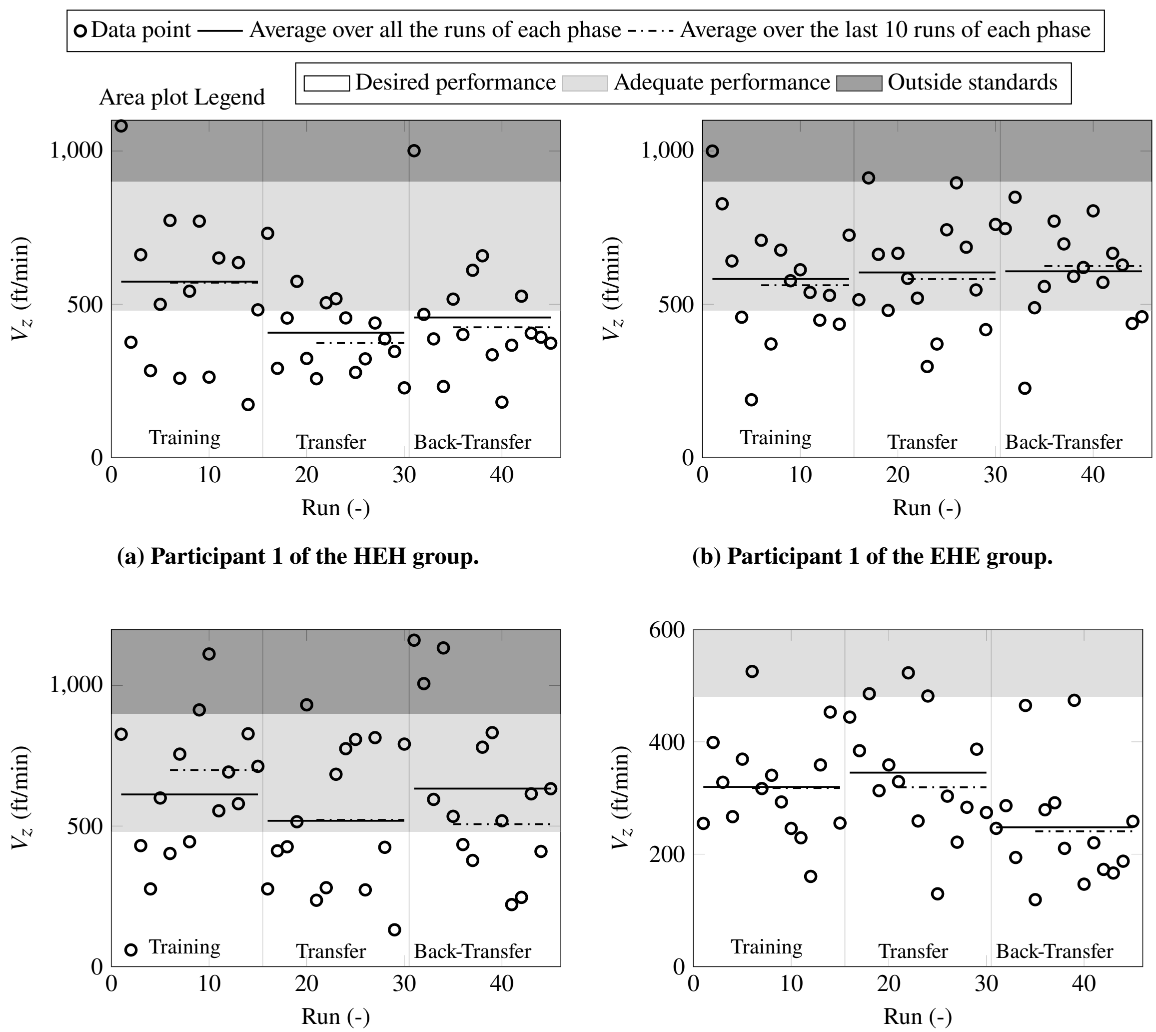
For the sake of brevity, the results presented in this paper are related only to the rate of descent at touchdown, which was identified as a key metric to corroborate our hypothesis. All the other metrics measuring performance at touchdown (Tab. 1), as well as those providing insight into the control strategies adopted by the participants of the two experiment groups, will be analyzed at the completion of the study.

Fig. 5 illustrates the rate of descent at touchdown throughout the experiment for the participants of the HEH group on the left hand side (Fig. 5a and 5c) and for those of the EHE group on the right hand side (Fig. 5b and 5d). For a real flying task like autorotation, there will always be a huge amount of variation between repetitions, so that spot measurements (i.e., looking at the pilot doing the maneuver only once) are not a statistically reliable indication of performance. For this reason, the average over all the runs of each phase (solid line) and the average over the last ten runs of each phase (dash-dotted line) are also represented in Fig. 5.

To ensure that averaging the data of the repeated trials does not cause any strange artifacts (e.g., masking learning effects), it is safer to consider the average over the last ten runs of each phase in the preliminary analysis of the results.

Both participants of the HEH group (Fig. 5a and 5c) show a substantial improvement in the rate of descent from the hard to the easy configuration (from training to transfer phase), whereas their performance are steady or deteriorate slightly from the easy to the hard configuration (from transfer to back-transfer phase).

Participant 1 of the EHE group (Fig. 5b) exhibit flat performance throughout the entire experiment, whereas Participant 2 of the EHE group (Fig. 5d) shows steady performance from the easy to the hard configuration (from training to transfer phase) and a notable improvement from the hard to the easy configuration (from transfer to back-transfer phase).



(a) Participant 1 of the HEH group.

(b) Participant 1 of the EHE group.

(c) Participant 2 of the HEH group.

(d) Participant 2 of the EHE group.

Fig. 5 Individual data points concerning the rate of descent at touchdown for each participant of each group.

IV. Conclusion

Current results are in line with previous experimental findings obtained for the same task but with a simpler helicopter model [14], according to which transfer occurs from the hard to the easy dynamics, but not the opposite. However, to confirm these preliminary results there is the need to test more subjects. Indeed, statistical tests can be conducted on a larger sample enabling to determine whether the differences identified from visual inspection of Fig. 5 are actually significant, thus strengthening the outcome of the experiment.

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