EFFECTS OF AN ECOLOGICAL INTERFACE ON FLIGHT TRAINING EFFECTIVENESS

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For Ecological Interface Design (EID), the underlying constraints and properties of an operator's work domain are analysed and used as a basis for the design of the information displays, so that these may reveal these underlying mechanisms. Most evaluations for EID have been performed with expert or trained participants. However, it can be hypothesised that the effects of EID will also change the way tasks are learned by novices; since the EID designs support direct manipulation, and at the same time show the constraints in the work domain, a novice would be able to perform the task as a skill, employing the direct manipulation features of the interface, while at the same time learning the underlying constraints from the work domain. Our interest is the effect of an EID display on skill acquisition in a flying task. To this end we evaluated the EID display by (Amelink, Mulder, van Paassen, & Flach, 2005) in a study with novice pilots, learning flight path and speed control of a simulated aircraft. It was found that initial performance by the EID group was better than by a control group, the EID group also showed more consistent and homogeneous behavior. The EID display did not lead to increased workload, as measured with the Rating Scale for Mental Effort. Asymptotic performance levels for both groups were not significantly different.

Introduction

In order to reduce the time and cost involved with flight training, flight simulators are becoming more commonly used. Much effort is being put into understanding the contribution of motion feedback and visual cues towards increasing the effectiveness of simulator-based pilot training (Mulder, Pleijsant, van der Vaart, & van Wieringen, 2000; Pool, Harder, & van Paassen, 2016). When using a simulator for initial training, alternative interfaces that increase the instructional value may be considered. It can be argued that interfaces based on Ecological Interface Design (EID) may be applied to this. Even though EID is mostly considered to "facilitate human adaptivity and flexibility to cope with unforeseen events" (Borst, Flach, & Ellerbroek, 2015), the way in which users are supported might also aid in the learning process. The effect of EID interfaces on learning received limited attention, two notable exceptions are a longitudinal study using the DURESS II process control microworld (Christoffersen, Hunter, & Vicente, 1996, 1998), and a series of experiments in which the Oz display – not designed by the EID approach, but as a functional aviation display – is evaluated (Smith, 2007; Smith, Boehm-Davis, & Chong, 2004).

The objective of this research is to evaluate the training effectiveness of EID interfaces during a manual control task, by comparing the skill acquisition for task-naive subjects using conventional instrumentation to those training with the total energy-based perspecive flight path display (Amelink et al., 2005). During an approach, or any other situation in which altitude and airspeed changes are requested, energy management is the underlying principle for the coordination between throttle and elevator. The pilot tries to control two aircraft states (airspeed and altitude) by using two control inputs (throttle and elevator) but these inputs do not directly map onto the controlled aircraft states. During flight training, pilots are often taught to apply a control strategy in which the inputs do directly map onto the outputs in order to simplify the control task. The two variations of these simplified control strategies are the "throttle-to-path & elevator-to-speed" and "throttle-to-speed & elevator-to-path" strategies. However, these simplified strategies are sub-optimal and lead to adverse control couplings (Lambregts, 1983; Langewiesche, 1944).

The experiment investigates whether the visualization of the aircraft's underlying energy relations supports student pilots in learning the basics of flight. The intention is to evaluate the EID display as a training tool, so the experiment uses a quasi transfer-of-training set-up, in which participants' performance is tested with the conventional display.

Total Energy-Based Perspective Flight-Path Display

The total-energy display is based on a tunnel-in-the-sky display, which shows a three-dimensional guidance situation with respect to the trajectory to be followed: "It allows a direct spatial orientation of the aircraft's position, attitude and motion relative to a fixed landmark -the tunnel geometry- in the environment" (Mulder, 1999). This

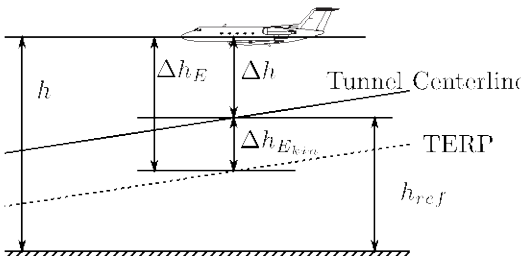


Figure 1: Definition of the Total Energy Reference Profile (TERP) (Amelink, Mulder, van Paassen, & Flach, 2005)

Figure 2: Human-Machine Interaction Laboratory (HMI-Lab) at Delft University of Technology

orientation and motion can also be interpreted as a visualization of potential (height) energy. In addition to the physical motion, the display also visualizes the energy inventory of the flight, by showing the Total Energy Reference Profile (TERP) and the Total Energy Angle (TEA). From the TERP and the tunnel visualizations, pilots can observe total energy, potential energy and kinetic energy deviations. Likewise, the TEA and the flight path angle show rates of these quantities (Figure 1).

Experiment

Goal of the experiment

The goal of the experiment is to evaluate the training effectiveness of the total energy-based perspective flight-path display during a manual flying task. In order to evaluate the training effectiveness, the skill acquisition of participants is compared to that of participants using a baseline tunnel-in-the-sky representation. Also, the natural progression of participants is the object of study, therefore the amount of feedback during training is limited as much as possible. This also means that task complexity had to be reduced, therefore the aircraft control was limited to purely longitudinal motion, effectively limiting flight training to climbs, descents, and straight-and-level flight.

Apparatus

The experiment was performed in the Human-Machine Interaction Laboratory (HMI-Lab) of the faculty of Aerospace Engineering at the Delft University of Technology (Figure 2). Subjects were able to control a six-degree of freedom, non-linear model of the Cessna Citation 500, by means of a right-handed electro-hydraulic side-stick and a throttle located to their left. The interface was presented by means of an 18-inch LCD monitor. The side-stick was configured such that only fore-aft movement was possible. Also, rudder control was disabled, flaps were kept to 15° and the landing gear remained retracted during the entire simulation. In terms of atmospheric models, zero wind was present but some turbulence was included. No outside visual was used in the experiment but engine sound was generated and the lights were dimmed during the experiment.

Participants

A total of 24 task-naive participants took part in the experiment, of which 20 male and 4 female. All participants indicated normal color vision and none of the participants had prior flying experience. All participants filled in the revised Study Preference Questionnaire (Jeske, Backhaus, & Rossnagel, 2014) before the experiment, in order to score participants based on the holist/serialist cognitive style division. The same questionnaire was completed by 110 pilots (RPL, PPL, and ATPL) in order to select participants such that both experimental groups were representative for a typical pilot population. In addition, participants were selected and divided over the two experimental groups in order to balance both groups as much as possible in terms of prior experience.

Control task

During the experiment, participants were asked to follow an altitude and airspeed profile along a longitudinal trajectory. A simulation run consists of a series of change in either: altitude, airspeed or a in knots combined change in altitude and airspeed. An example of this can be seen in Figure 3. The requested altitude profile

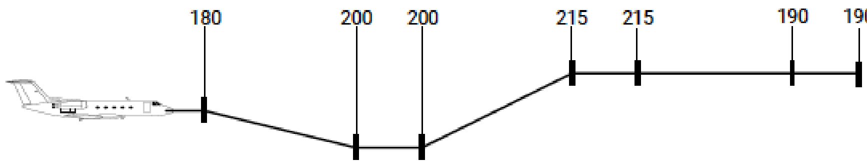


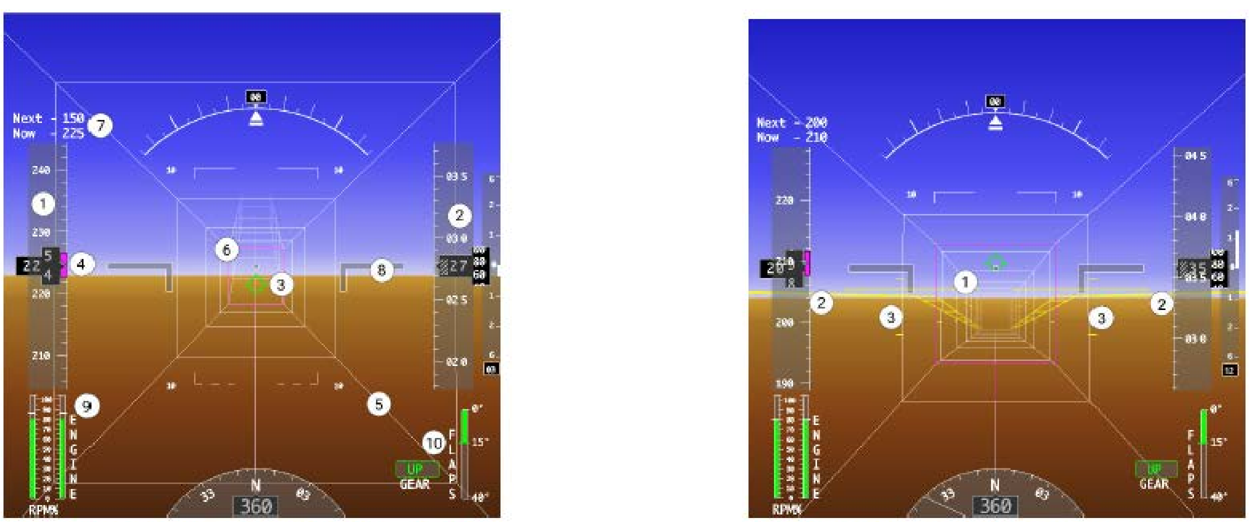
Figure 3: A section of the trajectory, indicating the requested altitude profile and the goal speeds in knots

is indicated by the tunnel-in-the-sky representation in both interfaces. The currently requested airspeed is indicated by the location of the speedbug and the current and following airspeed goals are also indicated numerically in the interfaces, both of which can be seen in Figure 4. Participants were told to control the aircraft through the tunnel and to follow the airspeed commands as accurately as possible. i.e., to minimize all occurring position and airspeed errors.

The simulation trajectory consisted of fifteen different changes in altitude and/or airspeed. After each requested change in either aircraft state, a section was always present where participants were requested to fly straight-and-level with a constant airspeed. Effectively doubling the amount of changes in aircraft state. This was done in order to allow participants some time to recover from any errors in the required aircraft state and thus to limit any error propagation through following sections of the trajectory. In order to avoid pattern recognition and boredom, the trajectory was split into three sections and the order was mixed according to Table 1. Between subjects there was no randomization performed, meaning that all subjects had the same order of trajectories as indicated in Table 1.

Experimental design

The experiment has a between-subjects design with a quasi-transfer-of-training manipulation. During this transfer-of-training experiment, there are two phases referred to as the training and transfer phase. The training phase consists of nine simulation runs carried out during the morning. In the afternoon, on the same day, participants completed another six simulation runs during the transfer phase, as can be seen in Figure 5. The control group, referred to as BASE, used the baseline tunnel-in-the-sky interface during the entire experiment. The other group, referred to as the EID group, used the total energy-based perspective flight-path interface in the training sessions and participants used the same baseline tunnel-in-the-sky interface. As each simulation run lasts approximately seven



(a) **Baseline Interface:** 1) Airspeed Tape, 2) Altitude Tape, 3) Flight Path Vector, 4) Speedbug, 5) Tunnel, 6) Purple Goal Frame, 7) Goal Speeds, 8) Aircraft Symbol, 9) Tachometer, 10) Flap and Gear Indicator

(b) **Total Energy-Based Perspective Flight-Path Display:** 1) Energy Angle, 2) Total Energy Reference Profile, 3) Speedmarks (± 2 knots)

Figure 4: The two interfaces that were used in the experiment, highlighting the various display elements.

minutes, a fifteen-minute break was scheduled after each block of three simulation runs, in order to avoid fatigue.

Each participant received an experimental briefing two days before the experiment, which also included a recap of the relevant theory of flight needed to complete the task. This included an explanation of the effect of the controls and a summary of the relevant material regarding straight-and-level flight, climbs, and descends according to the FAA's Instrument Flying Handbook (Anon., 2012). Before starting the experiment, there was room for questions regarding the theory of flight and the functioning of the interface, but no feedback was provided during the experiment except for explaining some display features.

Furthermore, the baseline group was explicitly told to use the throttle-to-speed, elevator-to-path control strategy. On the other hand, the EID group was explicitly told to use the throttle to control total energy and the elevator to control altitude. However, both groups received the same experimental briefing through which they were made aware of the different control strategies.

Table 1: Order of the sections A, B, and C of the trajectory for each simulation run

Run	Order	Run	Order
1	A-B-C	10	B-C-A
2	A-C-B	11	C-A-B
3	B-A-C	12	C-B-A
4	B-C-A	13	A-B-C
5	C-A-B	14	A-C-B
6	C-B-A	15	B-A-C
7	A-B-C		
8	A-C-B		
9	B-A-C		

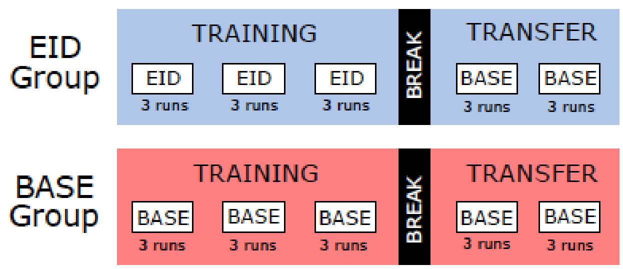


Figure 5: Experiment group definition, indicating which interfac was used by both groups during the experiment

Hypotheses

It was expected that the added energy information to the baseline tunnel-in-the-sky interface would increase mental effort during the training phase due to the apparent increase in display complexity as noted in previous evaluations of the EID display (Amelink et al., 2005). On the other hand it is expected that the EID group will perform initially better than the control group, however, with the expected amount of practice both groups might end at the same asymptotic level of performance, as measured in speed/altitude deviation. The EID group is also expected to have lower control activity, since the display information on energy and energy rate can resolve the cross-coupling between the control inputs and control target values.

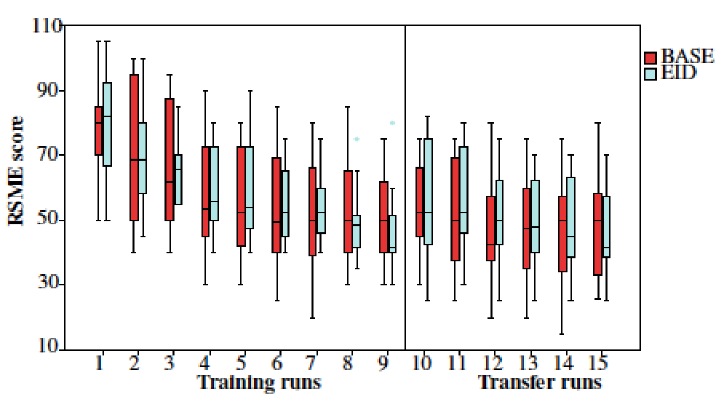


Figure 6: Boxplot of the experienced mental effort according to the Rating Scale Mental Effort, for each of the fifteen simulation runs for both the EID and baseline group. With simulation run 1-9 being the training phase, and 10-15 the transfer phase

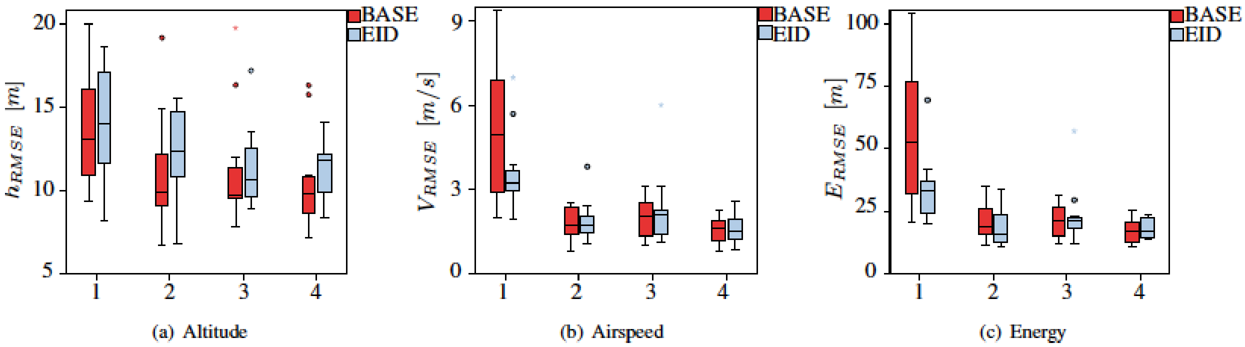


Figure 7: Boxplots of the performance measures, indicating: 1, the initial run; 2, the average scores for the last three runs of the training phase; 3, the first run after the transfer manipulation; and 4, the average scores for the last three runs of the training phase

Results and discussion

Mental Effort

The mental effort was measured with Zijlstra's RSME (Zijlstra, 1993). Previous evaluation with experienced pilots indicated a considerable increase in mental effort for the EID display. The results can be seen in Figure 6. A clear decrease over the runs is visible, but no significant difference between the two groups is present.between the final training run and the initial transfer run, a small increase in mental effort can be seen, however this was not statisticallly significant (Wilcoxon, $z = -1.735$; $p = 0.083$). There appears to be no difference in mental effort between the EID and baseline groups, indicating that the perceived complexity of the display as reported by expert pilots plays a smaller role in novices.

Performance

Values for the different performance measures are given in Figure 7. Overall, altitude tracking performance quickly reached proficient levels of performance and performance was adequate almost from the start of the experiment, resulting in only a small learning rate. The averaged performance in airspeed tracking of the two groups showed no significant differences (Wilcoxon, $z = -1.569$; $p = 0.117$), however the variance within the baseline group was significantly larger (Levene, $F = 6.004$; $p = 0.023$). Both groups reach the same level in airspeed tracking, even though the airspeed deviations are presented in a markedly different manner for the EID group.

The airspeed and total energy error both show larger errors for the first run only, however, asymptotic performance levels are quickly reached by both groups and by all participants. Regarding the total energy error, there is a significant difference between the two groups (Wilcoxon, $z = 1.961$; $p = 0.050$) and the associated variance of the EID group is significantly less than that of the Baseline group (Levene, $F = 8.385$; $p = 0.008$). When considering the average energy error for both groups in the final three training runs, or the final three evaluation runs, there were no significant differences. Thus both groups mastered energy control to a level that they were indistinguishable.

Conclusion

The flight-training effectiveness of an EID interface for learning a manual longitudinal flying task in a fixed-base simulator was evaluated by means of a between-subjects quasi-transfer-of-training experiment with 24 task-naive participants. Since the EID interface is considered for a training aid, the transfer is to a non-EID conventional interface.

Participants who trained with the EID interface showed better initial performance in terms of airspeed and total energy tracking, however these differences quickly disappeared. Also the variance between participants was significantly lower for the EID group. The usage of the EID interface also leads to an increase in control activity as evidenced by large elevator deflection rates and an increase in the number of throttle reversals. Contrary to expectation, since apparent display complexity is higher for the EID interface, there was no significant difference in terms of mental effort. The different interfaces did not result in a significant difference in performance once asymptotic performance levels were reached. There was no evidence of over-reliance on the energy cues by the EID group as there were no significant transfer effects. It appears that the functional information presented in the EID interface provide improved support during the initial phase of the training, without negative effects such as over-reliance on display features or increase in mental effort. In general, the effects of the EID display on performance were small, and only visible in the first few training runs. The evaluation did not include unanticipated situations for the participants, and thus did not test all aspects of the EID support. However, training benefits of EID displays might be larger for more complex systems that involve collaborative problem-solving and require higher order cognitive processes.

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