Implementing Energy Status in Head-Down Cockpit Displays: Impact of Augmented Energy Information on Pilot's Performance

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It is safety critical for pilots to be aware of the aircraft's energy state in terms of proper altitude and airspeed. A loss of energy awareness is an important human factors issue in modern civil aircraft. In order to maintain the energy awareness and support the manual flying skills, several cockpit display concepts suggest to augment the current energy status of the aircraft on primary flight displays in terms of the total energy angle. An experiment was carried out to determine which effect this additional energy information has on pilots' flight path control, instrument scanning, and situation awareness. Outcomes of the study show a significant shift of the scanning pattern from airspeed, altitude scale, and engine parameter towards the center of the primary flight display with unchanged situation awareness. In addition, pilots are better able to maintain given speed targets.

INTRODUCTION

Flying an aircraft manually, in principle, involves the management and proper distribution of energies. By manipulating the thrust of the engines, the pilot controls the total energy of the aircraft. This energy equals the sum of potential and kinetic energy. While the potential energy conforms to the altitude of the aircraft, the kinetic energy corresponds to its airspeed. In order to match flight path and speed demands, this energy, thus, needs to be distributed in a proper way through elevator movements.

To master the complexity of the management and distribution of energies, pilots usually follow what is referred to as “pitch-and-power” flying. In order to command a desired power setting, they use memorized pitch-and-power values available in manuals provided by the manufacturer. However, the specific values define the needed power settings and depend on the aircraft's altitude, speed, mass, and configuration. Since these values vary when the latter parameters change, it is almost impossible to memorize proper settings for each flight situation. Consequently, pilots often need to interpolate the required power setting based on some crucial values they remember. These interpolations then need to be further adapted on a trial-and-error basis, which requires close monitoring and cross-checking power, pitch, altitude, and speed. This makes pitch and power flying cognitively and perceptually demanding, particularly in non-routine or stress situations.

To support better maintenance of energy awareness and pitch-and-power flying, it has been proposed to integrate additional energy information within the primary flight display (PFD). A persuasive approach is the visualization of the total energy angel (TEA, aka potential flight path angle) in combination with the flight path angle (FPA) (Amelink, Mulder, van Paassen, & Flach, 2005; Lambregts, Rademarker, & Theunissen, 2008). TEA represents the rate of change of total energy, and FPA represents the rate of change of potential energy. The spatial relationship of TEA and FPA provides an emergent feature (Bennet & Flach, 2011) which directly indicates the current energy state and distribution of kinetic and potential energy. For example, the relative position of TEA and FPA, i.e. whether TEA is above or below FPA, provides direct information about whether the aircraft is gaining or losing speed. If both indicators converge, it implies that the aircraft is flying with constant speed. In addition, the FPA shows the angle of descent or climb in relation to the artificial horizon line and pitch ladder. If included in the PFD, this display concept also takes advantage of the proximity compatibility principle (Wickens, 2003). That is, all primary flight parameters needed to aviate safely are presented along with information about the relative distribution of kinetic and potential energy in close spatial proximity. This sort of augmented energy information has already been provided in modern head-up displays, but has not been integrated in current head-down instrumentation (Blaye, Roumes, Fornette, & Valot, 2002).

The objective of the present study was to investigate to what extent pilots would use augmented energy information in head-down displays for manual flight path control, and which effects such augmentation would have on instrument scanning effort and precision of flight path control when performing a given approach and landing task. For this purpose, two new displays were developed and integrated in a simulator cockpit. The first one included a modified PFD with added augmented energy information in terms of TEA and FPA. The TEA is shown as a green horizontal line and the FPA as a green circle with a center dot (Figure 1, left). The second display, referred to as *nxStatus* display (Figure 1, right), represented a new single display, which provided energy related information combined with information about the current performance limitations of the aircraft (see Müller, Schreiter, Manzey, & Luckner, 2015 for more detailed information on this display and its development).

It was expected that providing this augmented information would unload the pilots from applying pitch-and-power knowledge and enable an easier and more intuitive way to find the proper energy setting for a given flight path. To assess these expected consequences, we compared pilots' instrument scanning patterns and performance while flying a standard approach with classical instrumentation versus with the new display concept. In order to assess changes in instrument scanning, eye tracking was used. It was hypothesized that while flying with support of the new display concept scanning of traditional engine parameters would decrease and a certain amount of scanning the new nxStatus display would occur.

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In addition, we expected that the implementation of TEA and FPA in the center of the PFD would alter the scanning pattern within the PFD. By means of relative positions of TEA and FPA, the pilots directly receive information about relative changes of velocity and altitude, i.e. the current distribution of kinetic and potential energy. Therefore, the demand of scanning the speed and altitude scale as required for conventional pitch-and-power flying should decrease. Specifically, it was assumed that scanning of the air speed and altitude plus VS indicators would decrease in favor of more frequently scanning the center of the attitude director indicator (ADI), again compared to the scanning patterns during conventional manual flight.

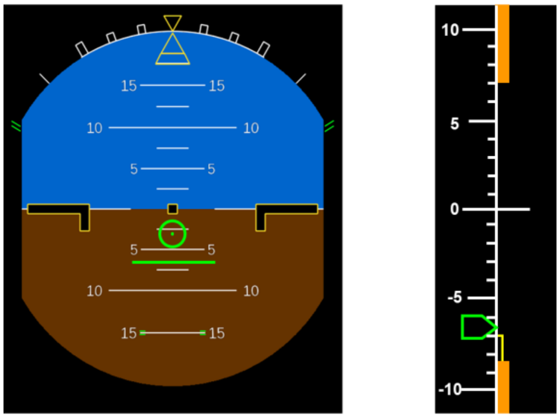

Figure 1: Center of PFD with augmented TEA and FPA (left); additional display: nxStatus scale (right)

With respect to performance, it was expected that the additional visual cues for flight path and speed control, displayed by the relations between TEA, FPA, and artificial horizon, would improve the overall flight performance in terms of meeting target altitudes and speeds more precisely.

However, from a human factors perspective, also possible new risks connected to the new display concept were considered. If the new display indeed would lead to changes of primary flight parameters in the expected way, this might also involve the risk of losing situation awareness with respect to speed and/or altitude. In order to consider this possible risk, a situation awareness assessment with respect to speed, altitude and VS, based on the Situation Awareness Global Assessment Technique (SAGAT), was included in the study design (Endsley, 1988). However, because we assumed that the new display just would reduce but not fully eliminate scanning of the primary flight parameters, we expected that situation awareness would not significantly change by using the new display concept.

METHOD

Participants

Eleven male certified pilots from commercial airlines with A320 type rating (two captains and nine first officers) participated in the study. Their age ranged from 27 to 55 years (*M* = 33.6, *SD* = 9.2) and they had between 770 and 14,560 flight hours experience (*M* = 4,371, *SD* = 4,559). All pilots had normal or corrected to normal vision. All participants volunteered their time to participate in the study.

Task

The participants' task was to perform a manual (raw data) approach and landing with a predefined flight procedure. The task started 20 NM from the threshold of the center runway in Frankfurt (FRA 25C) at 4,000 ft above mean sea level for a straight-in approach and landing with instrumented landing system. The moments of configuration and deceleration were standardized and fixed at defined distances to the threshold for better comparability.

The simulation started with an indicated airspeed of 250 knots and clean configuration of the aircraft. 18 NM from threshold the airspeed should be reduced to 220 knots; at 15 NM, the pilots should decelerate the aircraft to 180 knots and simultaneously configure the aircraft's landing flaps to Position 1. Flaps Position 2 should be initiated 13.7 NM before threshold. The intercept of the instrument landing system's glide slope was at 11.48 NM. Here, the pilots were supposed to steer the aircraft on a −3° descent while maintaining the indicated airspeed of 180 knots. 9 NM to the threshold the pilots should start decelerating to 160 knots and maintain the reached airspeed until 5 NM to threshold. At 6 NM they were supposed to lower the landing gear and configure to Flaps 3 and Flaps 4 (full configuration) in sequence. Starting 5 NM from threshold the aircraft should decelerate to 108 knots approach speed. All decelerations should be executed with idle thrust and initiated exactly at the given distance.

Apparatus

Simulation. The experiment was conducted in a fixed-base flight simulator equipped with a high quality visual system. The simulator was configured as a VFW614-ATD aircraft, which contains a flight control system with side-sticks similar to Airbus. Despite minor differences, e.g., in a higher aerodynamic drag, all relevant flight characteristics as well as the cockpit configuration corresponded closely to the ones of an Airbus A320. However, for the purpose of the present study, the standard cockpit layout of the simulator was supplemented by the display elements as described in the introduction. The PFD as well as the navigation display and the centralized display of engine parameters were presented on 10-inch monitors. The added nxStatus display was shown on a separate 7-inch portrait screen.

Eye tracker. SMI (SensoMotoric Instruments) Eye Tracking Glasses 1.9 and the software SMI iView ETG™ in version 2.1 beta were used for the recording of participants' eye movements.

Design

Each participant performed the approach and landing procedure with two different simulator configurations. The first configuration included the standard instrumentation complemented by the augmented display elements TEA and FPA in the PFD and the separate new nxStatus display. This configuration will be referred to as *nxDisplay* condition in the following. The second configuration corresponded to the standard cockpit instrumentation and will be referred to as *conventional* in the following. The sequence of performing the two approaches with the different simulator configurations was counterbalanced across participants.

Dependent Measures

Eye tracking. In order to investigate instrument scanning strategies, the relative dwell times on the different relevant displays and indicators were assessed. The relative dwell time was defined as the overall time that gazes were placed within the boundary of a certain area of interest (AOI) divided by the total duration of the scenario.

A total of five different AOIs was defined: (1) Engine Parameters. This AOI contained the indicators of fan speed (N1), exhaust gas temperature, fuel flow and core speed (N2) of both engines. (2) Speed. This AOI included the speed scale. Here, information like current indicated airspeed (IAS), selected speed, speed trend, and speed limits are displayed. (3) Altitude/VS. This AOI contains the altitude scale, VS indicator, and glide slope indicator. Thus, information like altitude, selected altitude, VS, and glide slope deviation are displayed in this area. Although it would have been good to separate between gaze on the altitude band and VS indicator the limited spatial resolution and precision of the eye-tracking system did not allow for a separated assessment of dwell times for these closely related displays. (4) ADI/Heading. This AOI represented the space between speed and altitude band, and comprised all information visible in the center of the PFD, including the ADI displaying the bank and pitch angle of the aircraft, as well as the heading and localizer deviation. In the nxDisplay configuration, also the augmented indicators for FPA and TEA were visible in this AOI. (5) nxStatus. This AOI corresponded to the new nxStatus display providing information about the current energy state and flight envelope. This AOI was only considered in the nxDisplay configuration. In addition to these five primary AOIs, all fixation times outside of these primary AOIs were aggregated and this dwell time was considered as a sixth variable in order to control the proportion of possible eye-movements not being related to the task in the different experimental conditions.

Situation awareness. Participants' situation awareness was assessed with an adjusted SAGAT (Endsley, 1988). When applying the SAGAT approach, the flight simulation was put into freeze at a fix point of 8 NM before the threshold while the display information were hidden. At this point, the pilots were decelerating to a given speed with idle thrust and tracking the glide slope. They were asked for six flight parameters: IAS, altitude, glide slope deviation, sink rate, pitch angle, and fan speed N1.

Situation awareness was assessed through the number of correct answers. An answer was considered as correct, if the pilot could successfully reproduce a parameter within given tolerance (Table 1).

To avoid effects on scanning patterns induced by the expectation of the situation awareness assessment, the SAGAT was conducted only once, after the last scenario of the experiment. Thus, situation awareness data are available only for parts of the participants ($n = 3$ flying with standard instrumentation, $n = 4$ flying with nxDisplay configuration).

Table 1: Flight parameter tolerances for successful SAGAT answer

Flight Parameter	Tolerance
IAS	±2.5 knots
Altitude	±100 ft
Glide Slope Deviation	±0.25 dots
Sink Rate	±100 ft/min
Pitch	±2°
N1	±5%

Performance. To investigate the impact of the differing display configuration on flight performance, we explored how precisely the pilots matched given altitude and IAS demands while flying with both simulator configurations. For this purpose, deviations of actual parameters from target parameters were quantified by means of root mean square error (RMSE) aggregated across time. In case of the parameter IAS, only sections with given constant speeds were used to calculate the RMSE.

Procedure

The study was structured into two phases. The first phase involved a familiarization of the pilots with the meaning and use of the new displays. This included a detailed standardized briefing and short practical demonstration of the functions and interpretation of the augmented energy information in the PFD as well as of the new nxStatus display. Afterwards, the pilots were supposed to perform several air work tasks in the simulator similar to the demands of the tasks used in the following experimental trials. Altogether, this familiarization phase took about 1.5 hours.

After a short break, the eye tracker glasses were calibrated and the pilots were briefed for the upcoming flight tasks. They were instructed to behave like during line operations in order to make performance in the simulator as similar as possible to real flight situations. In addition, acceptable tolerances for primary flight parameters were explained and the pilots were directed to maintain or reach the requested flight parameters as precisely as possible.

The following experimental blocks consisted of different flight tasks, which had to be performed with the two different configurations. Each block started with a short practice flight to accommodate participants to the specific simulator configuration followed by four short air work scenarios. Following the air work tasks, the approach and landing task had to be performed. Before the actual flying phase started, participants were briefed for this task including targets for configuration changes and flight parameters. The simulator was configured with retracted speedbrakes and flaps, and the thrust lever was set to a position equal to a steady and horizontal flight with 250 knots.

During the approach and landing task, an experiment assistant always served as pilot monitoring and supported participants in performing the task by selecting needed parameters, e.g. speed, altitude, and heading, at the autopilot control unit by request of the pilot flying, or executing ordered configuration changes. The pilot monitoring also did the common callouts and pointed out if flight parameters were out of tolerance.

Subsequently, the pilots were interviewed about their experience with the prototype. The debriefing interview was guided by pre-assembled questions, and participants were encouraged to comment their answers.

Data Analyses

The recorded eye movement data were further processed with the program SMI BeGaze™ version 3.5 beta. The data were manually offset corrected for every scenario, and all fixations within the scenarios were manually mapped on a fixed reference image with the specified areas of interest.

Statistical analyses of the eye-tracking and performance data from the two experimental conditions were performed by pairwise t-tests. An alpha-level of .05 was defined in order to consider possible effects as significant. The non-parametric Mann-Whitney U-test was used to compare the situation awareness data based on the reduced sample size. Because this testing involved the testing of a null-hypothesis the alpha-level was raised to .20 for this particular testing.

RESULTS

Eye Tracking

Mean dwell times for the different AOIs and configurations are shown in Figure 2. As becomes evident from this figure, the display configuration entailed a clear effect on instrument scanning behavior. As expected, the nxDisplay configuration led pilots to reduce their dwell times on the engine parameters. Whereas participants checked the engine display for about 2.6% of the overall flight time with conventional instrumentation, this already small percentage was further reduced to a negligible 0.7% when flying with nxDisplay configuration, $t(10) = 4.08$, $p = .002$, $\eta_p^2 = .62$. This effect was expected because the new displays were meant to free the pilots from traditional pitch-and-power flying and the need to find proper thrust settings based on the inspection of the engine parameter. The fact that a small but considerable percentage of time was invested to inspect the new nxDisplay configuration ($M = 1.8$) provides evidence that participants really made use of the new energy information in this condition.

Also in line with our expectations are the changes of instrument scanning behavior which emerged for the different indicators included in the PFD. Compared to the conventional setup, the relative dwell time on the speed scale decreased in simulator configuration nxDisplay compared to conventional configuration from $M = 13.3\%$ to $M = 9.8\%$, $t(10) = 5.35$, $p < .001$, $\eta_p^2 = .741$. This was expected, since the relative change of speed (e.g. while stabilizing the target speed) can directly be derived from the augmented display elements TEA and FPA. Similarly, also a slight decrease of the relative dwell times on the altitude scale, VS, and glide slope indicator was found when flying with the nxDisplay compared to conventional instrumentation ($M = 16.9\%$ vs. $M = 19.6\%$). Yet, this effect just failed to reach the conventional level of statistical significance, $t(10) = 1.92$, $p < .083$, $\eta_p^2 = .27$. These decrements of dwell times on the speed and altitude indicators when flying with the new displays were compensated by a significant increase of dwell times on the ADI, i.e. the center of the PFD where also the augmented energy information in terms of TEA and FPA were provided (conventional: $M = 30.5\%$; nxDisplay: $M = 41.3\%$), $t(10) = -4.39$, $p = .001$, $\eta_p^2 = .66$.

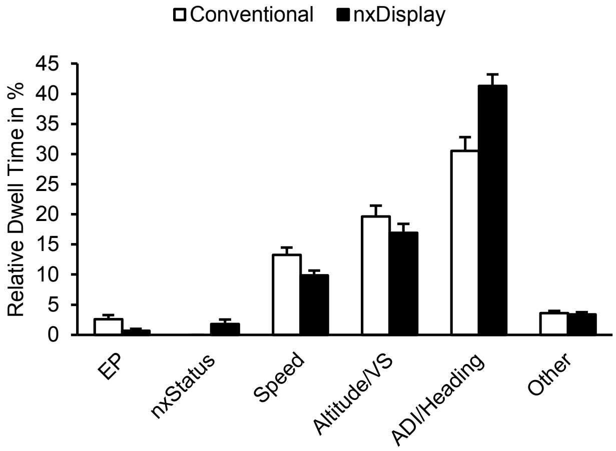

Figure 2: Average relative dwell time of all AOI across both configurations

Performance

The RMSE measures used to assess pilots' performance in matching target altitudes and speeds during the approach and landing task revealed no significant differences for altitude (conventional: 40.7 ft; nxDisplay: 38.1 ft), $t(10) = 0.73$, $p = .48$. Obviously, participants were equally able to keep altitude targets independent of the configuration. The RMSE for indicated air speed was only calculated in sections with given constant target speeds. This measure revealed that the nxDisplay configuration made it easier to keep the actual aircraft's speed closely to the target speed. Whereas the RMSE for speed was 2.16 knots when flying with the conventional configuration it was reduced to 1.60 knots when augmented energy indicators were provided, $t(10) = 2.40$, $p = .04$, $\eta_p^2 = .37$.

Situation Awareness

No obvious difference between the two configurations emerged for the situation awareness assessments. In the condition with the conventional instrumentation participants provided on average 3.0 correct answers. When flying with the nxDisplay configuration the mean number of correct answers was slightly higher (3.5); yet this difference is far from reaching statistical significance, even if a raised alpha level is considered because of the null-hypothesis testing (Mann-Whitney $U = 4.50$, $p = .77$).

DISCUSSION

The current study was conducted in order to analyze possible consequences of providing augmented energy status information within the PFD of commercial aircraft on pilots' performance in flight path control, instrument scanning and situation awareness. It was expected that providing this information would better support pilot's energy awareness in manual flying of an aircraft, which, basically, requires finding proper pitch-and-power settings. Thus far, pitch-and-power flying requires pilots to select suitable settings from memory and adjust them if necessary based on repeated cross-checks of the relevant flight parameters, i.e. airspeed, pitch, altitude, VS, and engine speed. In order to better support this task, a concept was proposed that included a visual presentation of TEA and FPA within the PFD, as well as a new separate nxStatus display. The format of presenting this information in the PFD was chosen in order to provide important information on the distribution of kinetic and potential energy in the aircraft as a sort of emergent feature. It was expected that providing this information would enable pilots to find proper settings more quickly and with less scanning of different instruments, thus improving flight path and speed control.

The eye tracking results support the stated hypotheses regarding the changed instrument scanning behavior. Specifically, when flying with the augmented energy displays the pilots reduced scanning and cross-checking of speed, altitude/VS, and engine speed (N1) compared to flying with conventional instrumentation, and showed longer dwell times on the center of the PFD where the augmented energy information was provided. This provides direct evidence that the pilots accepted and used the display concept and its energy feature after a relatively short training and accommodation phase in comparison to the traditional transition trainings. Furthermore it suggests that pilots were unloaded from cross-checking and cognitively evaluating the information from different indicators in order to arrive at a proper power setting needed for flying the given flight path with a required attitude and velocity. With the new display elements added to the conventional head-down instrumentation, the most important energy relevant information needed to aviate safely and precisely could be directly gathered from an emergent feature in the center of the PFD which was formed by the spatial relations of TEA, FPA, and artificial horizon. At the same time, the shift of attention to the center of the PFD induced by the PFD was not so strong as to impair situation awareness for the relevant flight parameters like speed and altitude. This became evident from the SAGAT data.

Providing the additional energy information did not only change scanning demands but also enabled pilots to meet the requested speeds during the approach and landing task more precisely. However, the pilots' performance of maintaining a given altitude profile was not improved compared to the conventional configuration. This might be due to the relatively low precision requirements, especially at the beginning of the glide slope. In evaluating the performance effects, it should be taken into account that the approach and landing task used as a model in this study did not provide a particular difficult challenge for the experienced participants. It is supposed that even more benefits of the augmented energy information would emerge, also reflected in less altitude deviations, if more complex and more demanding flight tasks had to be performed.

The lack of studies including comparative systems (e.g. Lambregts et al., 2008; Amelink et al., 2005) makes it difficult to bring the results of our experiment in context. Overall, the current results can be taken as an empirical proof that pilots can make effective use of additional energy information when provided as part of head-down instrumentation. It encourages to consider augmented energy information not only as a tool used for head-up displays but also as an enrichment of the conventional head-down PFD.

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