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Improving Precision Vertical Flight Operations Through a Direct-Perception–Action Display

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Despite advances in head-up display technology, pilots of vertical takeoff and landing air and spacecraft still rely heavily on visual perceptual cues for precision landings. Reliance on these cues hampers operational success because exogenous influences such as brownouts can significantly reduce the effectiveness of perceptual cues, often with little warning. Moreover, the hover and descent-to-landing phases of vertical flight constitute the highest workload phases of flight for these pilots. To mitigate the reliance on visual perceptual cues and reduce mental workload, an integrated head-up display is proposed that leverages ecological perception through a direct-perception–action visual representation, called the vertical altitude and velocity indicator. By allowing operators to directly perceive system states instead of deriving them, the vertical altitude and velocity indicator allows operators to employ more efficient processes of perception rather than relying on memory, integration, and inference, which are cognitively demanding. Experimental results demonstrate that the vertical altitude and velocity indicator improves pilot performance and reduces subjective workload, particularly in expert pilot populations, as compared with a conventional head-up display. Implications for training and unmanned vehicle operations are also discussed.

Nomenclature

a = actual
d = desired
F = F test, the ratio of two independent chi-square variables divided by their respective degrees of freedom
p = probability of observing the same or larger difference in means
n = total number of observations
α = level of statistical significance

I. Introduction

THE vertical descent-to-landing phase represents one of the most difficult aircraft maneuvers that vertical takeoff and landing (VTOL) air and rotorcraft pilots face. Unfortunately, although great strides have been made in visual precision-landing aiding devices for pilots of conventional takeoff and landing aircraft, little progress has been made in providing similar visual landing aids for VTOL air and rotorcraft. This shortcoming has been particularly problematic for recent military operations in desert environments because of brownouts (also known as dustouts), which cause a significant reduction in visibility due to dust and sand forced into the air by rotors or jet exhaust close to the ground during the final portions of a vertical descent.

The loss of critical visual perceptual cues, which are currently the primary landing aid for VTOL air and rotorcraft pilots, is exacerbated by ground effect, vortex-ring states, and meteorological flying conditions. These conditions require the pilot to focus his or her attention on instruments, and previous research has shown that controlling sink rates due to ground effect is a source of high workload for VTOL pilots [1]. For rotorcraft pilots, transition through the vortex-ring state (when a rotorcraft descends into its own downwash vortices, disrupting lift), can cause a loss of control and stability. Both ground-effect and vortex-ring states cause pilots to be especially concerned with their descent rates, requiring additional dependence on their instruments. This divided attention across internal and external cockpit cues causes high workload. Finally, operating in instrument meteorological conditions such as with low ceilings and poor visibility adds to this high workload, because visual cues are not as readily available. For a comprehensive review of human factors issues in vertical flight operations, see [2].

To aid pilots in landings as well as other flight phases, current VTOL and helicopter flight displays employ head-up displays (HUDs) that collimate images of flight symbology or sensor video onto a piece of semireflecting glass such that important pieces of information are overlaid directly on the outside view of the world [3]. HUDs eliminate the need for visual scanning and refocusing of the eyes from the instruments in the cockpit to the outside world view. HUDs are a critical technology for vertical landings because quick access to outside visual cues is paramount to vertical landings, and the display of altitude, vertical speed, attitude, and heading are the most commonly monitored flight parameters in these settings. However, currently employed flight displays in helicopters and VTOL aircraft present critical flight information as disparate elements across the display. Figure 1 illustrates the HUD used in the AV-8B Harrier V/STOL (vertical short takeoff and landing) aircraft [4]. Of particular note, vertical speed and altitude are depicted separately, and altitude is only a digital readout, whereas vertical speed is both a digital and analog depiction. Particularly for the vertical landing and hover tasks, this lack of proximity and presentation of raw data require significant cognitive processing in a time-critical task that can cause high mental workload and increase the chance for possible errors.

To reduce the high cognitive workload of vertical flight, particularly in unfavorable operating conditions, intuitive and perception-based displays should be used for quick and effortless processing. We propose that a decision support tool that satisfies this need by taking advantage of direct-perception interaction via ecological perception can help mitigate the vertical flight challenges. Ecological perception occurs when there is a high correlation between some cue and the external environment such that information is transmitted to an operator through perception, which is fast and effortless and can occur in parallel with other mental processes, unlike analytical cognition, which is slow and error-prone [5]. A example of an ecologic perception display is the use of blue sky and brown earth in a primary flight display, which makes it immediately clear to the pilot that the

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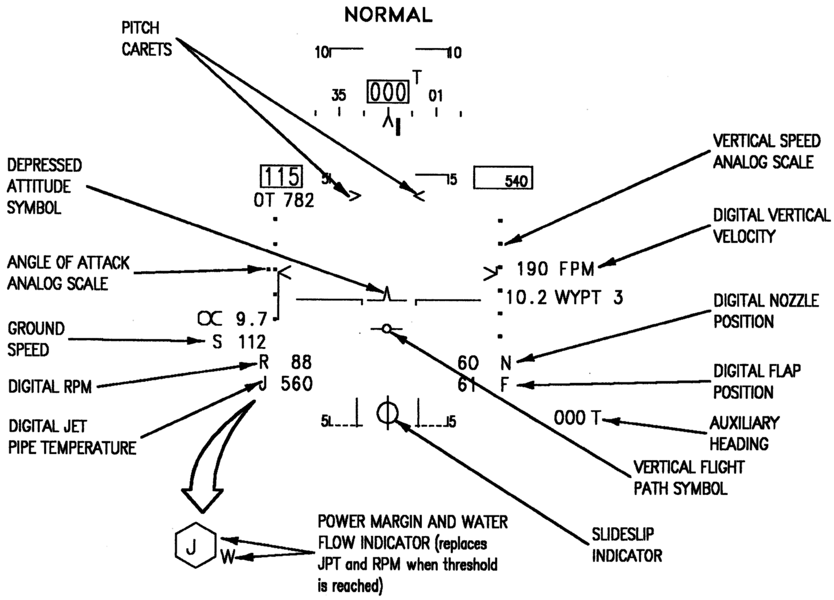


Fig. 1 Harrier HUD [4].

attitude is either nose-up or nose-down, without the pilot having to search for the hash marks and specific numbers that indicate this nose position.

Previous research has shown that direct-perception–action visual representations improve performance because operators employ the more efficient processes of perception rather than the cognitively demanding processes involved when relying on memory, integration, and inference [6–8]. We propose that such a direct-perception ecologically valid display for VTOL air and rotorcraft will significantly improve vertical flight performance, because it will reduce cognitive workload.

This reduction in cognitive workload is essentially an order-reduction problem. In a physical system, it has been shown that reducing the order of the system will improve human performance in terms of manual control and that presentation of state variables is critical so that operators can make predictions about system response [9]. We propose that a display that not only presents critical state variables, but that also integrates them in a preatttentive, ecologic fashion reduces the *perceived* order of the system. Displaying certain state variables is unquestionably an order-reduction technique, but how they are displayed, as we will show in this paper, can significantly improve operator performance, particularly when they are designed to leverage direct-perception–action interaction. In the remainder of the paper, we will present a cognitive model for the vertical flight and hover domain, propose a HUD display that effectively reduces the perceived order and complexity of the problem, and then discuss experimental results to test these hypotheses.

II. Vertical Flight Cognitive Model

A cognitive-task analysis (CTA) was performed to gain a better understanding of pilots' cognitive processes, key challenges, and those flight parameters most crucial during a vertical landing. The cognitive-task analysis used for this research included interviews with various helicopter, Harrier, and Osprey pilots, who were both interviewed and observed in simulators in the hover and landing flight phases. Apollo engineers, ground controller personnel, and several Apollo astronauts were also interviewed. Because landings on the moon were (and will be) conducted in the vertical flight regime, information gathered from such interviews was useful. In addition, analysis of the Apollo Lunar Surface Journal was conducted to better understand lunar vertical landings. Details of the CTA can be found in [10].

As a result of the CTA, a model of situation awareness (SA) was developed to illustrate the cognitive processes that are required for achieving SA for pilots or astronauts performing vertical landings or hover operations. Situation awareness is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [11]. The model, illustrated in Fig. 2, captures the key elements of SA for the vertical landing and hover flight phases, which flow directly into decision-making and action implementation, including a feedback loop.

A. External Inputs

The external inputs to the cognitive model highlighted in Fig. 2 emphasize the primary sources of information that pilots rely on to determine their current position in relation to their goals [12]. The three input sources include 1) visual (information provided by the outside view of the world), 2) vestibular (information provided by changes in gravitational forces on the body), and 3) symbolic (information provided by flight instruments and displays within the cockpit).

The visual inputs specific to vertical operations include such information sources as geographic and man-made landmarks, shadows, dust, and the horizon. Landmarks provide key peripheral and depth-perception cues that indicate vehicle height. The familiarity with the objects in conjunction with the visual feedback they provide in terms of texture and detail provides a sense of vehicle position relative to the ground to ensure current and future ground clearance.

The pilot's vestibular system, located in the inner ear, responds to gravity to sense angular motion, accelerations, and position [13]. In vertical operations, this system is important for sensing lateral, vertical, and angular motion as well as any acceleration in those directions to maintain a hover or descent with minimal lateral or longitudinal motion. However, the vestibular system can be misleading or unreliable [13]. The symbolic information, or the presentation of that information within the cockpit, is often unique to the vehicle platform, as seen in Fig. 1. because visual and vestibular feedback can provide erroneous cues, the symbolic information displayed through these flight instruments is a critical input for achieving high situation awareness.

B. Internal Inputs

First and foremost, the goals of the mission drive the cognitive processes of the pilots in a top-down fashion. In the case of vertical precision landing and/or hover operations, the two foremost goals are safety and mission success. Safety is dependent on many factors, however, those that correspond directly to vertical landing and hovering include maintaining a safe attitude (i.e., staying within the

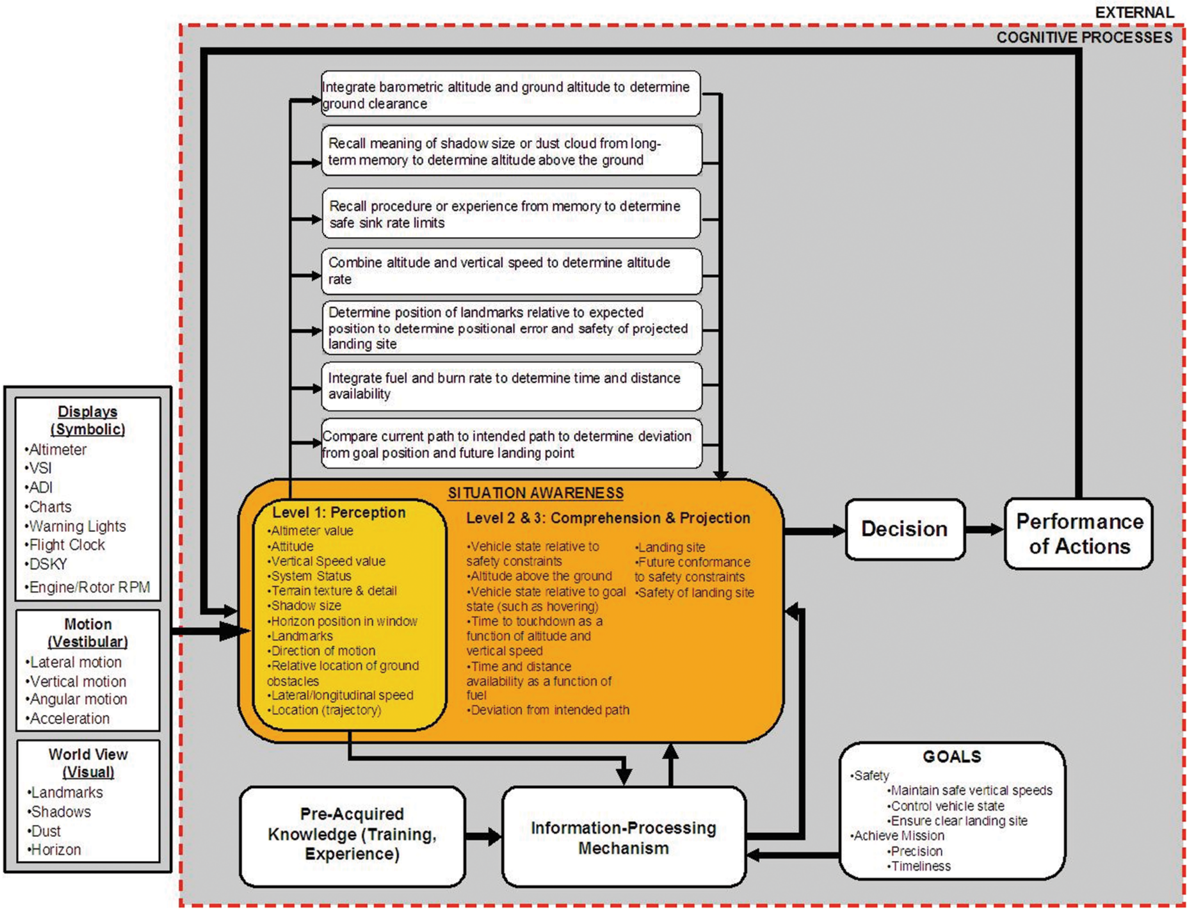


Fig. 2 Cognitive model for hovers and vertical landings (ADI denotes the attitude indicator).

pitch and bank constraints of the vehicle), safe descent rates, and an obstacle-free landing zone. Mission success for precision landing can be directly measured by the accuracy and safety of the operations and the timeliness, which can be critical in many space and military operations.

Although mission success and safety are the primary goals, their implementation is affected by how well pilots maintain SA, which is driven by internal cognitive inputs from long-term or working memory, and so any preacquired knowledge gained through training or experience is of key importance. As discussed previously, there are three levels of SA, with the first level addressing the perception of the environment [11]. This information comes directly from the three primary external sources described previously, but as noted, they can often be unreliable.

Comprehension of the current situation is the second level of situation awareness. At this level, the integration of level 1 information and the external goals creates an understanding of those perceived elements with respect to the relevant goals [11]. During this stage, pilots compensate for missing or segregated information by relying on memory and information processing to get them from the information they can directly perceive to the information they actually need to achieve their goals. For example, because current vertical speed indications do not indicate sink-rate constraints for safe descents, the comprehension of this information requires that pilots recall from memory a heuristic taught in training (generally, to not exceed a descent rate greater than the current altitude). The practice of teaching safe descent heuristics was uncovered through the cognitive-task analysis. Unfortunately, the greater the mismatch in the information available and the information needed to achieve the goals, the higher the cognitive workload required to perform information processing and recall from memory. In interviews conducted with Harrier, Osprey, and helicopter pilots, they reported that referring to this heuristic was an error-prone and mentally taxing step, because they had to compare the dynamic sink rate (which may only involve perceiving a digital number on the display) to the known heuristic, while compensating for the rapidly changing value.

The third and highest level of SA is the projection of the comprehended information into the future. Projection is achieved when an understanding of the perceived attributes and the dynamics of the specific environment can be extended into an understanding of a future state relative to the goals [14]. Performing vertical landings requires tightly coupled comprehension and projection due to the highly dynamic nature of this phase of flight. Because the time constants are short and part of true understanding involves projecting into the future, these two steps are essentially concurrent. In other words, because this is a manual control task during which flight parameters are changing in fractions of a second, the extent of the pilot's projection of vehicle state into the future is limited because it is happening almost concurrently with the comprehension.

Critical information that pilots must be able to project into the future are the approximate touchdown point and the safety of that site. To determine the landing site, pilots must combine rate and position information and project it into the future. Likewise, determining the safety of a projected landing site involves mentally comparing the perceived and comprehended relative position of obstacles and hazards with the projected landing site to assess the safety situation. In the model illustrated in Fig. 2, these mental steps are highlighted from level 1 to levels 2 and 3 SA.

Given the information required to promote all three levels of SA as depicted in Fig. 2, a display was designed to address the limitation of current designs in meeting these requirements, presented in the next section.

III. Vertical Altitude and Velocity Indicator

A. Design Requirements

The cognitive-task analysis and development of the cognitive processing model revealed that current vertical landing displays require high cognitive workload and introduce error by requiring pilots to mentally integrate information and perform calculations. More specifically, a mismatch between the data provided by current instruments and the information needed by pilots to ensure a safe and precise landing became apparent. We hypothesized that integrating information to provide a salient display of the information required in a form that matches the mental model of the pilot and provides for direct-perception interaction should significantly improve vertical landing operations. We propose that in support of the cognitive model outlined in Fig. 2, any vertical flight decision support display should do the following:

1) Provide obvious display of sink-rate safety constraints and a means for attaining pilot attention when the constraints are violated. Any lag associated with vertical speed measurement needs to be eliminated to provide reliable information [15].

2) Enable direct perception of the combination of vehicle altitude and vertical speed to assist in quickly determining vehicle hover state.

3) Display vehicle altitude above the ground as the primary displayed altitude during vertical operations. This height, as opposed to the altitude above sea level, is of primary concern during a descent.

4) Display the approximate time to touchdown. The integration of vertical speed and altitude during a vertical descent should be done by the automation to remove this cognitively demanding step that can be critical for time-sensitive operations.

The vertical altitude and velocity indicator (VAVI) was developed to address the challenges and design requirements described previously. The purpose of the VAVI is to help minimize the intermediary cognitive processes that are currently required to get from perception to comprehension and projection levels of SA by directly conveying altitude and vertical velocity information to indicate unsafe situations and hover maneuvers in an integrated form with salient cues. It is intended to be used during hover and vertical descent operations. Figure 3 illustrates the VAVI in the context of a whole display. The VAVI provides an intuitive integrated flight instrument display that leverages ecological perception. It consists of four major parts: altitude scale, vertical speed indicator, vertical speed needle and symmetric counterpart, and a clock. The VAVI is intended to be used in conjunction with other flight instrument displays.

The center vertical shaft is a fixed altitude bar in units of feet. The range of the altitude is dependent on the altitude at which an aircraft or spacecraft would initiate a vertical descent or hover. The small gray box at 95 ft outlines the current altitude as a digital value that will slide along the analog altitude scale accordingly. This feature provides high precision while maintaining the analog representation of altitude. In this version of the VAVI, when the altitude exceeds 500 ft, the gray box will remain at the top of the fixed bar, whereas the digital value inside the box will continue to increase consistently with the current altitude above the ground. The half-circle to the right of the altitude bar is the vertical velocity gauge in units of feet per minute (fpm), and depicts vertical speeds between ±500 fpm. This limit was selected because the cognitive-task analysis revealed that pilots are instructed to not exceed 500 fpm in the descent-to-land phase. The arms of the VAVI refer to the vertical speed needle (the right arm) and its symmetric counterpart (the left arm). This vertical speed indicator (VSI) moves as a unit vertically along the altitude bar such that the arms always protrude from the current altitude, and the two arms are always symmetric.

In conjunction with the altitude bar, the VSI needle of the graphical display is a visually prominent element that maps directly to critical system states, such that the position of the needle provides a cue as to what state the vehicle is in, including hover maneuvers and precision descents. Therefore, the arms are cues that provide state information at a glance. Nominal ascent, hover, and descent maneuvers are illustrated in Figs. 4a–4c, respectively. Instead of mentally combining the altitude and vertical speed in an effortful approach to determine the vehicle state, the vehicle state is made perceptually obvious. The VAVI VSI arms, in conjunction with the altitude bar, provide an ecologic depiction of vehicle hover state and are an example of an emergent feature that supports high-level global perception [16], because the arms give an immediate representation of trend (up or down) and magnitude of change. The VAVI arms are highly salient features that provide critical vehicle state information with a glance and correspond to specific goal-relevant states such as hovering or descending at a specific rate. The VAVI also uses the proximity compatibility principle, which states that to the extent that information sources must be integrated, there will be a benefit to presenting those sources either close together, in an objectlike format, or by configuring them to create emergent features [17].

Although Fig. 4 shows the current instantiation, the VAVI was originally conceived for future lunar landing operations [18], which will require a similar vertical descent-to-land profile [19]. The most significant difference between the original lunar VAVI and the current design is a reversal of the arms: that is, in a lunar descent, the arms point down instead of up. The original design included this arm-down profile to be consistent with the principle of the moving part [20], in that the arms pointed down while going down. However, in preliminary pilot testing with helicopter and Harrier pilots, all stated that this orientation conflicted with their mental model of the VSI indicator, thus the change was made to the current VAVI design seen in Figs. 3 and 4.

Another key feature of the VSI element of the VAVI is the inclusion of an unsafe sink-rate (negative vertical speed) zone, which is dynamic to provide a more sensitive depiction of the current descent-profile safe limits. The lower half of the VAVI semicircle will turn red if an unsafe sink rate is detected for the current altitude, vehicle, and environmental conditions. When the vertical speed limit is violated, the red zone becomes a brighter red (as seen in Fig. 4d, depicted in grayscale). By including this dynamic unsafe zone, which is updated as the descent rate is increased or decreased (i.e., the red zone in the lower half of the integrated VSI grows or shrinks as a function of both operator input and proximity to the ground), pilots no longer need to rely on heuristics that require them to recall rules from memory to determine current vehicle limits.

The box below the altitude bar in Figs. 4c and 4d is the estimated time to touchdown as a function of the current altitude and current sink rate and only appears when the vertical speed is negative, indicating a descent. For time- or fuel-sensitive operations, this piece of information can be critical. In the past, this calculation has been a rough estimate based on the integration of altitude and vertical speed information over time. By providing this information directly over time, as will be demonstrated in the experiment in the next section,

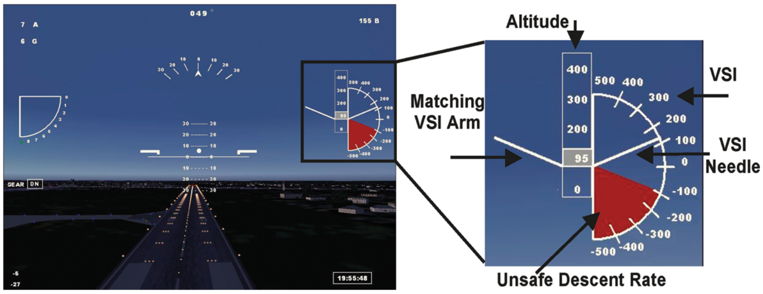
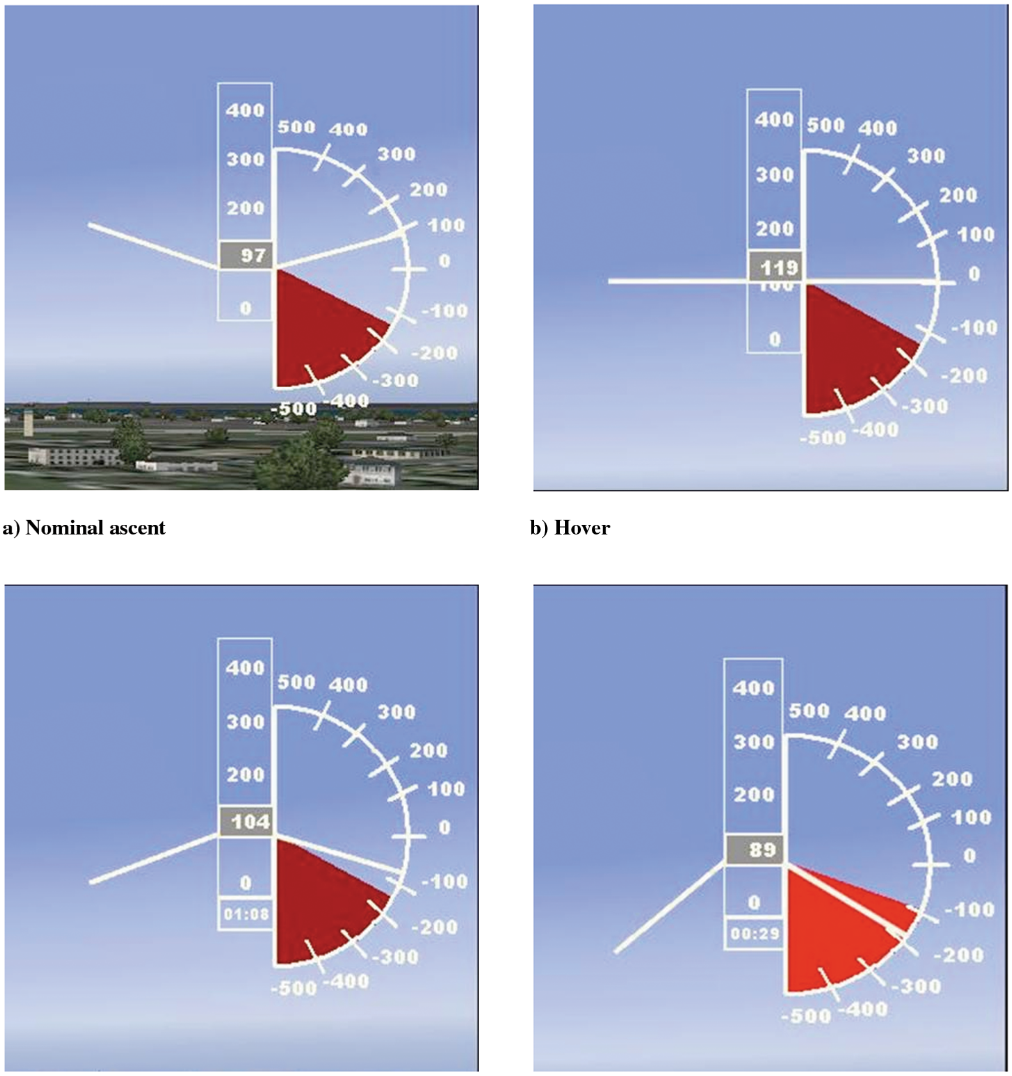


Fig. 3 VAVI in context.



a) Nominal ascent b) Hover

c) Nominal descent d) Unsafe descent

Fig. 4 VAVI phases of flight.

mental workload can be reduced by using lower levels of cognitive control to discern goal-relevant information.

This integrated flight instrument is designed for an aircraft equipped with a radar altimeter and Global Positioning System (GPS) sensors to provide accurate altitude and positional hover accuracy. The VAVI will be most effective when implemented with an instantaneous vertical speed indicator, which displays vertical speed without the time lag normally experienced with the use of a conventional vertical speed indicator. Moreover, the above-ground-level (AGL) presentation should not be slaved directly to the radar altimeter, due to known problems with erratic readings that cause jumps in the arms, particularly in uneven terrain settings such as choppy seas. Such a response would be an unnecessary distraction to the pilot. Rather, the AGL reading should be a smoothed combination of the radar altimeter and GPS signals. This approach has been shown to be effective for precision fixed-wing landings [21,22] and was recently demonstrated for helicopter vertical landings in the Defense Advanced Research Projects Agency's Sandblaster program [23].

B. Order Reduction in the Cognitive Model

The cognitive model in Fig. 2 illustrates the mental steps required to comprehend the perception of raw data from the outside world, displays, and vestibular systems with respect to safety and mission goals using the instruments currently employed for vertical flight operations. In contrast, the introduction and implementation of the VAVI encourages preattentive processing and direct-perception–action interaction through salient information coding and emergent features created by the object integration of altitude and vertical speed information.

With use of the VAVI, pilots can directly perceive the vehicle state relative to the safety constraints and instantaneous goals, the time to touchdown as a function of instantaneous altitude and vertical speed, altitude above the ground, and the vehicle state relative to the goal state. Thus, level 1 SA is improved by effectively eliminating the mentally taxing and often error-prone tasks associated with retrieving from long-term and working memory to get to SA levels 2 and 3. Figure 5 illustrates how the cognitive model changes when the VAVI is used as opposed to conventional displays. With use of the VAVI, the need for raw data indicators such as a separate altimeter and vertical speed indicator is eliminated and replaced. In addition, the VAVI provides salient cues to relative (analog) and exact (digital) positional information, making it easy to quickly glance and comprehend the vehicle state relative to the goal state. Therefore, this step from perception to comprehension is eliminated with use of the VAVI, as is the perception of the altimeter value and vertical speed indicator value.

The direct display of unsafe sink-rate constraints in the VAVI eliminates the need for a mental heuristic taught or learned through training that occupies an unnecessary human channel of information processing. In particular, the use of the red unsafe sink region in

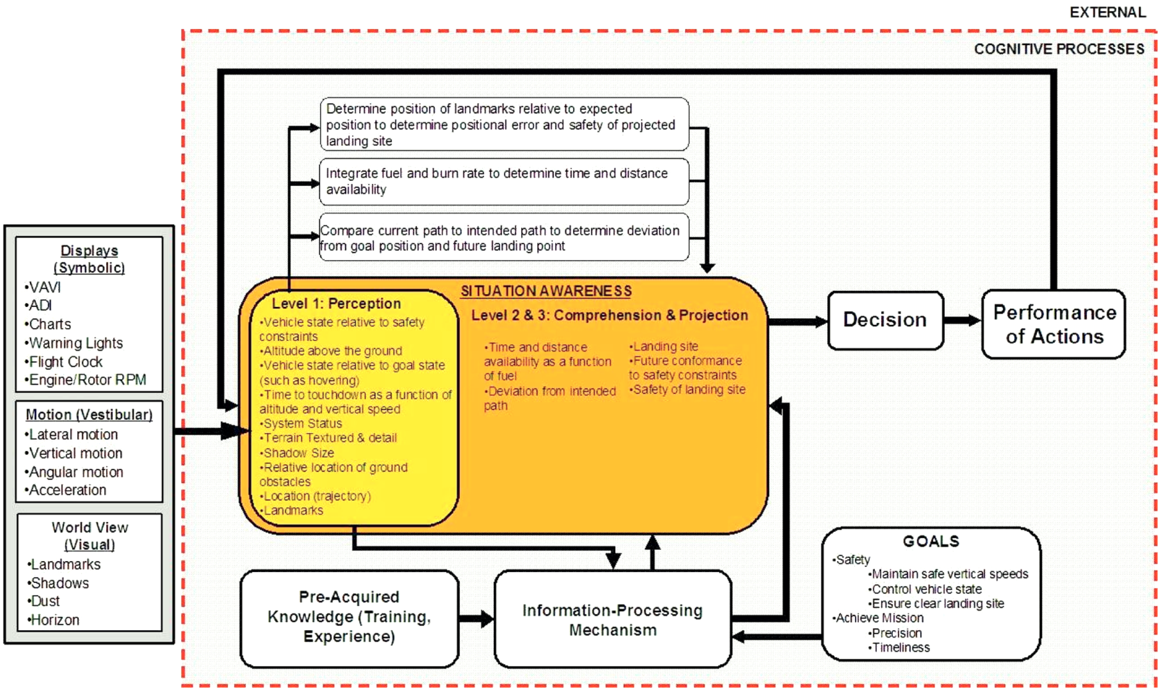


Fig. 5 Cognitive model with VAVI.

conjunction with the parallel VAVI arms promotes preattentive processing, which allows pilots the ability to see this critical relationship in approximately 200 ms, which takes significantly longer when a pilot has to read a VSI display, cross check the VSI with the altimeter, and recall the safe descent heuristic, all to determine what the VAVI shows instantaneously. In addition, by directly displaying altitude above the ground, this critical piece of information is salient and clearly displayed in an integrated fashion with other key parameters. Therefore, pilots do not need to integrate barometric and ground altitude to determine altitude above the ground. Finally, by allowing the automation to do the integration of altitude and vertical speed to estimate time to touchdown, this cognitive step is eliminated.

By eliminating these mental computations, the VAVI enables direct perception of key information, which should significantly reduce pilot mental workload. For example, the VAVI enables perception of the vehicle state relative to the safety constraints, thus moving it from level 2 SA to level 1. Similarly, the vehicle state relative to a goal state such as hovering is directly perceived, as is the time to touchdown and altitude above the ground. Although terrain texture and shadow size will still be perceived and processed to provide additional altitude information, that same information could be directly perceived via the VAVI. Thus, the VAVI aids in precision landings because it replaces a pilot's need for unreliable external cues. Moreover, the VAVI creates a mental reserve that can be applied to more critical tasks in the demanding vertical flight regime that displays and automation cannot directly address.

IV. Experimental Validation

Numerous previous studies have shown that human performance can improve when displays use direct-perception–action visual representations that allow users to employ the more efficient processes of perception rather than the cognitively demanding processes that rely on memory, integration, and inference (e.g., [8,24,25]). Thus, we conducted an experiment with the hypothesis that the VAVI would improve performance in vertical flight operations over traditional conventional displays.

A. Experimental Apparatus

A commercial flight simulation software package (Microsoft Flight Simulator 2004) was modified to display the VAVI in a simulated V/STOL aircraft HUD. Specifically, the Abacus Military Aircraft Collector's Edition expansion pack was used to simulate an AV-8B Harrier V/STOL jet aircraft. Two Harrier HUDs were created, modeled after an actual Harrier head-up display: one with the VAVI (Fig. 3) and one without the VAVI (Fig. 1). The VAVI display replaced any analog or digital representations of vertical velocity and radar altitude used in the HUD without the VAVI.

The hardware consisted of a Dell OptiPlex GX520 with an Intel Pentium 4 3.40 GHz processor and an Intel 83945G Express Chipset family graphics card, a Dell 19 in. flat-panel monitor ($1152\times$ 864 pixels and 16-bit color resolution), and a Saitek X45 digital joystick and throttle control with CH Products CH Pro rudder pedals. System audio was provided using standard workstation speakers. All flight parameter data were recorded once per second using an additional data recorder add-in software package and were exported to a spreadsheet program for postexperiment processing. The measures taken from this large data set are discussed in the Results section.

B. Participants and Procedure

A total of 31 participants volunteered for this experiment (28 men and 3 women). The participant population included aviation-focused students, recreational pilots, and professional pilots. Of those 31 participants, 9 (8 men and 1 female) did not meet training proficiency levels (discussed in the following procedure section) and did not move on to the test scenarios. Participants were compensated for their participation with a university logo t-shirt and refreshments. The age range of qualifying participants was 12–63 years, with an average age of 34. Eight of the participants had both fixed-wing and rotor-wing pilot experience, 3 had rotor-wing-only experience, and 3 had fixed-wing-only experience. A total of 8 had only PC-flight simulator experience. Of the 14 that had actual flight experience, 9 of them also had PC-flight simulator experience. The number of hours of experience in each participant's most experienced platform (rotor-wing, fixed-wing, or PC simulator) ranged from 15–9000, with the median of 300 h and a mean of 1175 h.

All participants completed an approximately 15 min tutorial about the specifics of their display (VAVI or no VAVI) and then were given a series of training lessons to learn to fly the simulated Harrier. This training was approximately 1 h, at which time participants were asked to demonstrate their proficiency at each of the specified tasks (hovering and vertical landings). Proficiency was based on ability to maintain a commanded hover altitude within a ± 10 ft tolerance for 30 s and the ability to land at a specified location, perform a controlled descent, and not crash.

Following the training and demonstration of proficiency, participants completed two test scenarios, each lasting approximately 10 min. Before beginning the tests, participants were informed that their performance during takeoff and straight-and-level portions of flight would not be measured, but hovering and vertical landing performance would be measured. Participants were presented the two test scenarios in randomized order to prevent a possible order effect. At the completion of each test scenario, participants filled out a 10-point subjective mental workload survey based on the NASA-TLX [26], with 1 corresponding to minimal-to-no mental workload and 10 corresponding to the highest mental workload the participant has ever experienced. This univariate metric was selected because the goal was to obtain a global assessment of workload after each test scenario, which is deemed to be more sensitive than multivariate measures in these settings [27].

Finally, participants were asked to discuss what they liked and disliked about their respective displays and to provide recommendations for improvements. The two test scenarios followed by the workload scales took a total of 30 min on average. The entire experiment took roughly 90 min total.

During testing, key flight parameters such as altitude, heading, pitch, bank, vertical velocity, airspeed, latitude and longitude, and others were recorded to a data log file every second using flight data recorder software. The experimenter also observed each test participant during their test scenarios and noted any interesting behavior, including gaze or focus, body posture, and comments made throughout or during a specific task.

C. Test Scenarios

Two test scenarios were designed for this experiment, with both starting a flight from T.F. Green Airport in Providence, Rhode Island (PVD), to Logan International Airport in Boston, Massachusetts (BOS). This route was chosen for its relatively short distance and a very-high-frequency omnidirectional range navigation system, which made finding the airport very simple. The flight between Providence and Boston, after takeoff and before hover and landing, lasted approximately 4 min. This allowed participants to relax after takeoff and prepare for the landing, yet not expend too much time on the straight-and-level portion of flight, which was not of interest in this experiment.

The target landing site at Logan International Airport was a helipad 100 m in diameter located between the two main runways and marked by a white circle with a large H in the middle. The center of the helipad was the target landing site. Every scenario was conducted at dusk in a simulated summer environment. This operating condition was chosen for the following reasons:

1) The dark blue sky at dusk provided better contrast with the white HUD components, making it clearer for the participants.

2) The diminishment of visual cues at this time of day in conjunction with the already-reduced visual cues provided by a simulated synthetic outside view replicated an environment in which instruments are more critical for hovering and landing tasks.

In both scenarios, participants were asked to maintain a specific heading to get to the Boston airport. However, the two test scenarios varied slightly during the vertical descent phase. The primary differences were the altitude at which the participants were asked to hover and the descent rate they were asked to maintain. Both scenarios included a stationary hover (at different altitudes); one scenario asked the participants to maintain a constant static descent rate of -100 fpm to the landing site, and the other required a dynamic sink rate that matched the heuristic previously discussed (e.g., a vehicle at 150 ft should not sink any faster than 150 ft).

The experiment was designed to test the effectiveness of the VAVI for improving hover and landing performance and decreasing mental workload, as compared with a conventional HUD. The ability to maintain a constant hover altitude was hypothesized to be most influenced by the emergent features (namely, the arms of the VAVI) that indicate hover state tied directly to the hover altitude. A hover situation is clearly illustrated by outstretched and level VAVI arms. Likewise, capturing an accurate hover altitude (e.g., stopping at a prespecified altitude) is supported by the VAVI arms, which are horizontal when a hover has been achieved.

In this experiment, vertical landing performance was a function of two parameters: the ability to maintain an accurate descent rate and a safe descent rate. As the VAVI directly indicates safe descent rate limits and alerts the pilots of violations through a change in color, it was expected that the VAVI would result in fewer violations of the safe descent rubric. Likewise, because the arms of the VAVI indicate both a relative vertical speed direction and rate on an analog scale, with exact values displayed making it simple to realize the appropriate direction of control input for correction, the ability to maintain a prespecified safe sink rate should improve with use of the VAVI over a conventional display.

D. Experimental Design

This experiment was a mixed-design study, which was within subjects on the flight task factor (hovering versus landing) and between subjects on the display factor (conventional HUD or HUD with the VAVI). Several dependent variables were used in this experiment to measure hover and landing performance and workload, which included hover precision, vertical speed precision, and subjective workload. Each of these variables is described subsequently.

Hover precision, the ability to maintain a specified hover altitude, was captured for a specified 20 s window using a root-mean-square error (rmse) approach (the smaller the rmse, the better the performance), which is a common measure of success that gives the error value the same dimensionality as the actual and desired values [28].

Vertical speed precision, the ability to maintain both a dynamic and static descent rate, was also measured using rmse from the completion of a hover to landing. For the commanded static descent rate, participants were penalized for deviations greater than 10% of the commanded 100 fpm descent rate. For the dynamic sink rate, penalties were only assessed for any vertical speed outside of a 10 fpm range around the dynamic sink rate determined by the current altitude.

V. Results

The experiment included a primary independent variable: a head-up display instrument (VAVI or conventional) across different flight tasks of hovering and landing. Within the landing phase of flight, performance under static and dynamic descent conditions was measured. Because the dependent measures used to measure hover performance were not always extendable to landing performance, the general linear model used for this analysis included both single- and two-factor analysis of variance as applicable. For all reported results, $\alpha = 0.05$ unless stated otherwise.

For the hover-precision-dependent variable, a one-way analysis of variance (ANOVA) performed on the rmse [Eq. (1)] of the hover altitude during the specified 20 s window indicated no significant difference in hover precision between the VAVI and the conventional displays ($F(1, 34) = 1.484$ and $p = 0.231$). A square-root transformation of the data was required to meet homogeneity and normality assumptions:

$$\mathrm{RMSE} = \sqrt{\frac{\sum (\mathrm{HA}_a - \mathrm{HA}_d)^2}{n}} \tag{1}$$

For vertical speed precision, the rmse of vertical descent speed was analyzed as a 2×2 ANOVA, treating flight display (VAVI or no VAVI) as the primary factor and the commanded vertical speed (dynamic or static) as the secondary factor [also Eq. (1), with hover altitude (HA) replaced by vertical speed (VS)]. Participants were asked to hold a constant (static) vertical speed or a changing (dynamic) vertical speed during their descent. A reciprocal transformation of the data was necessary to meet homogeneity and normality requirements. Depicted in Fig. 6a, the rmse of vertical speed was

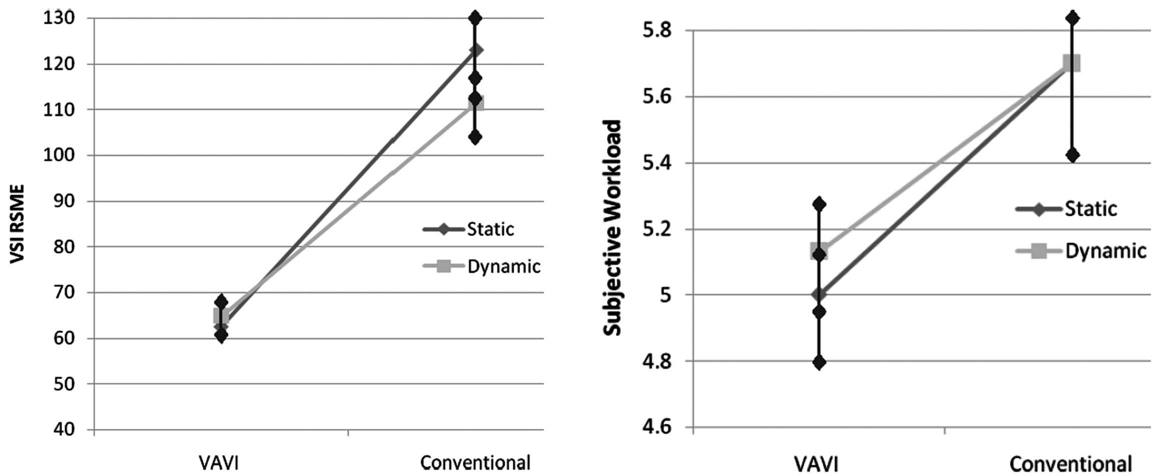


Fig. 6 Results for a) vertical speed precision and b) subjective workload.

significantly lower with the VAVI display ($F(1, 30) = 5.484$ and $p = 0.026$), but there was no significant difference between the precision of the static and dynamic vertical speeds ($F(1, 30) = 0.023$ and $p = 0.879$). There was no significant interaction between the factors. Thus, the VAVI promoted overall better vertical speed precision, and participants were consistent in their performance when holding a constant or variable descent rate.

For the subjective workload measure, a 10-point Likert scale with 10 as the highest mental workload and 1 representing minimal-to-no mental workload and a nonparametric Mann–Whitney U test revealed that the VAVI produced marginally significant lower perceived workload ($p = 0.108$). Figure 6b illustrates the reduced trend toward lower subjective workload with the use of the VAVI.

A. Expert Analysis

Although the initial analysis results were encouraging, given the short training time and large variation in participant experience, we examined the results of the top three performers from each flight display group (VAVI and conventional display). This subset analysis more closely represents the use of these displays in operational aircraft, because these participants demonstrated expert flight performance. Although we recognize that a true expert in these settings would have thousands of hours of vertical flight experience, we define expert in this experiment as subjects who were proficient and exhibited a superior skill set as compared with the novices. Using only those six participants who set themselves apart from the majority of the participants, the dependent measures discussed previously were analyzed. Nonparametric analyses were used for all dependent measures due to the small numbers of this participant subset, and so $\alpha = 0.1$, which is typical for such conservative tests.

With this expert subset, hover precision (Fig. 7a) showed a marginally significant difference in flight displays (Mann–Whitney U test, $p = 0.126$), such that expert users with the VAVI showed improved ability to maintain a desired hover altitude, as compared with those with the conventional display.

Vertical speed precision remained significant (Mann–Whitney U test, $p = 0.015$) between flight displays in this expert subset, with insignificance between static and dynamic commanded vertical speeds (Wilcoxon signed rank test, $p = 0.600$). As expected, the overall magnitude of the variation of experts' vertical speed control was better than the larger population (at approximately half), indicating that our selected top performers were indeed experts. Moreover, the consistent VAVI results between the static and dynamic vertical speed scenarios indicate that although the control of a dynamic vertical speed is more difficult than that of a static vertical speed, the VAVI makes both tasks consistently easier, as illustrated by better performance and significantly less variation in Fig. 7b. This result is important, as it has important training implications that will be discussed in the next section.

Finally, subjective workload results showed a statistically significant difference between flight displays in this expert subset (Mann–Whitney U test, $p = 0.026$) as compared with a marginally significant difference in the larger participant pool ($p = 0.108$), with no significance for the vertical speed condition (Wilcoxon signed rank test, $p = 0.157$). As illustrated in Fig. 7c, when participants have adequate training and are comfortable with the vertical landing tasks, workload is reduced with use of the VAVI. One interesting result is the comparison of subjective workload between the conventional displays in the larger population as compared with the expert subset. The experts clearly thought the workload was much higher with the conventional display (on the order of 25% more).

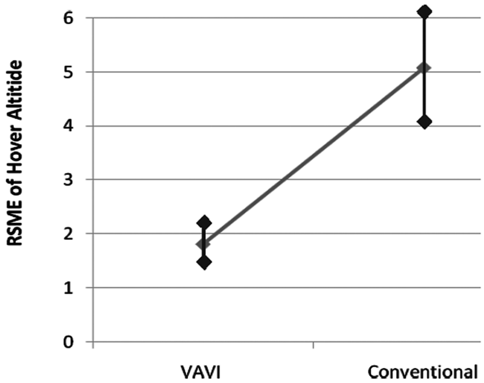
B. Participants' Recommendations for Improvements

Once all testing sessions were complete, participants were asked to comment on whether their display supported the hovering and descent tasks and what they would improve about their particular display to make the task easier and safer. Several participants in the conventional display group commented on the difficulties in dividing their attention across the numerous important variables. One participant in this conventional display category, who had not seen the VAVI, commented that "the trick is to be able to see instantly, the position of things." In addition, several of these participants specifically indicated the need for some sort of unsafe sink-rate alerting method. Interestingly, the majority of comments pertaining to possible conventional display improvements were directly addressed in the VAVI design.

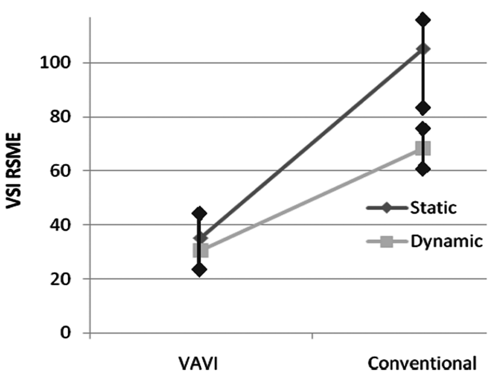
In contrast to the conventional display, those participants who used the VAVI indicated that they found several characteristics very helpful. Specifically, many of the participants reported that the red zone depicting unsafe sink rates jumped out at them when it changed color and indicated a necessary increase in throttle. Thus, the VAVI indicated not only the system constraints, but also mapped to a specific control input to fix the vertical speed violation. This observation further supports the model in Fig. 5, which illustrates the cognitive order reduction such that operators can see and react almost instantaneously, without any mental computation to determine an appropriate action for a potentially unsafe state.

When asked about the VAVI design (specifically, the dual arms that arguably present redundant information), roughly half of the participants indicated that they only used the right arm, and the other half said they used both arms of the VAVI as a unit. Of those that used both, several indicated that they used it in the periphery of their vision and that their positioning was helpful in directing attention to critical events, as well as maintaining a hover. Of those that did not use the left arm, only one found the left arm distracting.

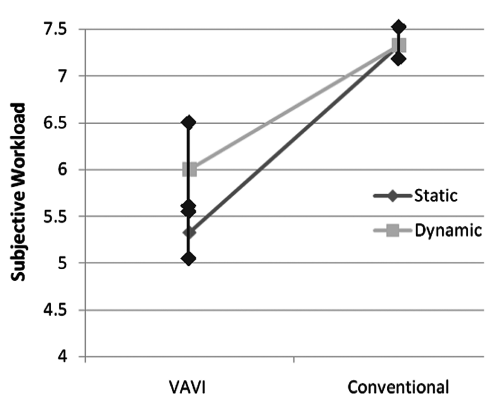
One design limitation uncovered through these debriefs was difficulty in interpretation when the VAVI needles were in the either full up or full down position (i.e., at greater than 500 fpm or less than



a) Hover precision



b) Vertical speed precision



c) Subjective workload

Fig. 7 Expert results.

−500 fpm). In addition, several participants asked for a precision lateral control display, which was added in a later revision and is the subject of current research.

VI. Discussion

The cognitive model for vertical landing and hover operations in Fig. 2 illustrates the numerous mentally demanding steps required to proceed through the levels of situation awareness and act accordingly, given current state-of-the-art technology. Through enabling direct-perception action, we hypothesized that the VAVI would promote order reduction such that cognitive processing would be minimized, as depicted in Fig. 5, which was supported through our experimental results.

In terms of whether the VAVI aided in the hovering task, whereas the results for hover precision were not significant in the larger 22-participant pool, they were marginally statistically significant for a conservative nonparametric test for the expert pool. These results indicate that the VAVI was somewhat helpful in the hovering task, particularly for experts. However, these results should be interpreted in light of the small sample of participants.

When examining the impact of the VAVI on controlled vertical descent, the VAVI contributed to significantly improved performance with both the subjects and the experts, who showed a 50% decrease in vertical speed control variation with the use of the VAVI. As expected, when the vertical speed indicator was integrated with the altitude display, and with the aid of the parallel VSI arms, pilots were able to detect and correct VSI deviations with the VAVI more effectively than with the conventional display with disparate information sources.

The experience of the pilots is equally as important as the actual flight performance metrics, and our results clearly illustrate that pilots subjectively experienced significantly less mental workload with the VAVI than with the conventional display. Moreover, the difference in workload perception between the expert subjects using the VAVI and the conventional display was dramatic, indicating an even more pronounced disparity between the two displays, given subject matter expertise. Because subjective workload is a reliable indicator of overall workload with high construct validity [29], these results confirm what the cognitive model in Fig. 5 suggests: that the VAVI effectively integrates information and reduces cognitive effort.

One important implication of these results, in conjunction with the cognitive model depicted in Figs. 2 and 5, is the impact on training. Training and preacquired knowledge are critical variables that impact the success of any decision support tool. Moreover, cost and time to train are important human-systems integration concerns, and so any tool that could significantly reduce these, in addition to improving overall flight performance, would be a valuable asset. Although the results reported here demonstrate that the VAVI reduces workload and improves performance, particularly for subject matter experts, given that the VAVI theoretically reduces cognitive workload and simplifies the task, the VAVI should improve novice performance.

To investigate this, a pilot study was conducted to determine the impact of the VAVI on novice performance, and and the results are reported elsewhere in detail [30], they are encouraging in that those pilots trained with the VAVI generally performed better than pilots trained in the same amount of time on a conventional display. Although these results are preliminary due to the small number of participants (12), and a larger study is needed to determine minimal acceptable training times and other relevant performance metrics, they suggest that the VAVI can improve not only expert pilot performance, but that training time can also be reduced.

Finally, there are important implications for the use of a direct-perception–action display such as the VAVI for vertical takeoff and landing of unmanned aerial vehicles (UAVs). Because the VAVI was designed to replace the need for visual perceptual cues for pilots in the cockpit, it can also be used by pilots or operators remotely guiding UAVs in vertical flight. Thus, the VAVI concept is one that promotes vertical flight operations, regardless of the point of control. Such a display would be particularly effective in perch-and-stare missions in which operators need the ability to slightly adjust vehicle parameters to conduct intelligence, surveillance, and reconnaissance operations. This is also the subject of current research.

VII. Conclusions

There is an increasing requirement for precision vertical landing capability for air and spacecraft, which is driven by the advantages of vertical takeoff and landing capability as well as improvements in sensor and control technology. However, vertical flight presents numerous control challenges that often involve the loss of outside visual perceptual cues or high mental workload when controlling flight parameters within tight constraints. Current flight instrument displays attempt to mitigate these challenges, but still require significant cognitive processing and lack perceptual decision aids specifically for hovering and landing tasks.

The vertical altitude and velocity indicator (VAVI), designed to address these challenges, demonstrated its ability to reduce pilot mental workload and improve performance of precision vertical operations in a laboratory setting. The VAVI appears to provide smoother control of vertical speed during landing by enabling direct-perception action of the current vehicle state, as well as improved hover precision. As compared with conventional displays, it also provides unambiguous situation awareness of vehicle state, including large deviations from intended states and possible constraint violations. Moreover, although objective performance metrics indicate trends in improved performance with the VAVI, subjective workload results indicate a significant improvement for expert pilots.

Most important, the VAVI may improve the safety of vertical landings and hovering because it explicitly represents unsafe flight regimes. The VAVI also creates cognitive reserves that can be applied to the mission rather than to the lower-level control of the aircraft, which is particularly important in UAV operations [31]. In addition, because the VAVI reduces the cognitive load on the pilot, it may be able to reduce training time, which has substantial operational and cost implications.

Current design improvements for the VAVI include a more obvious display of the vertical speed direction, investigation of the need for the left arm as well as an acceleration cue, integration of lateral and heading cues, and the use of user-generated flight cues such as hovering altitude bugs. Research is also underway to transition the VAVI into a UAV setting in the Aurora GoldenEye to determine its effectiveness in unmanned operations.

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